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13. ABSTRACT *(Maximum 200 words)*

This research program is directed toward the development of markedly improved high performance displays, designed to enhance diagnosis in digital mammography. The activities of the second year centered on the delivery and first use of the instrumentation for the experimental investigation of the novel cathodoluminescent materials.

(1) The demountable display tube and its associated vacuum system and electronic control was delivered, installed and used for the first time. It permits investigation of samples of the novel cathodoluminescent materials and their respective substrates with respect to characteristic display performance measures.

(2) Three CsI samples were ordered from the University of California at Berkeley delivered and evaluated in the demountable display tube.

(3) A theoretical study was done and found that the combination of cathodo-luminescence and electro-luminescence in the same display tube can lead to displays with higher brightness than conventional displays. The result of this study is presented in the Appendix of this report as a proposal to be submitted to NIH.

(4) Based on the fact that the work to be done in this project has not been completed by any means, it is requested to extend this project without cost for one year.

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Hoover Rodriguez 06/11/99

PI - Signature Date

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I. Introduction:

This research project is concerned with digital mammography and its thrust to improve on diagnostic performance using soft copy display compared to "state of the art" radiographic film-light box mammography. An essential component of digital mammography that will be critical to its success, is the high performance display from which diagnosis is to be carried out. The research is aimed at the development of a new generation of vastly improved high performance displays to meet the needs of mammography.

CRTs have already become an integral part of the diagnostic radiology department. Efforts are underway to investigate the suitability of high-resolution CRTs for primary diagnosis by the radiologist [1]. In fact the US Armed Forces have begun a program designed to accelerate the proliferation of digital imaging methods including primary diagnosis using softcopy displays. The Medical Diagnostic Imaging Support (MDIS) program is a Department of Defense Project to implement filmless radiology at military medical facilities [2] and there are studies emerging from Universities [3]. Initial results appear to be encouraging, even though serious questions remain. A recent workshop on problems of softcopy displays for use in digital mammography, organized by the Office of Women's Health [4] testifies that the medical community as well as the Federal Government is focussing its attention on the problem of finding adequate softcopy displays for primary diagnosis. Problems addressed during this workshop included optimization of the display-observer interface and standardization.

CRT displays have been undergoing intense development over the past 10-15 years and research on new display devices as well as development of new display devices is underway [5,6]. A specialty of our research program at the University of Arizona is to provide a quantitative measure of display performance [7,8, 9]. We have measured many of the best displays available over the past 5 years. This has led to the realization that their performance is far from ideal and significant improvement is unlikely if the traditional CRT structure, the faceplate and the deposition of the granular phosphor in a binder on this faceplate, is not changed. It is the objective of this research project to investigate means to improve softcopy displays

II. Body of the Report:

A. The instrumentation for the experimental investigation

1. Demountable display station

Central to our experimental program is a demountable display station. It was acquired from the Teltron Corporation in Birdsboro, PA.

The objective of the demountable display station is to permit analysis of a variety of luminescent samples. The particular features of the demountable display station are discussed with reference to Fig. 1. through Fig. 8.

Fig 1. is a schematic describing essentially the demountable display tube.

Fig. 2 is a photograph of the actual sealed off 3" display tube (upper left) and of one of the demountable 3" display tubes, delivered for this program (upper right). This photograph also shows 2 CsI samples in plastic bags (lower left), which were evaluated in one of the demountable tubes. Furthermore the photograph shows the metal rings, which hold the phosphor samples in the demountable tube.

Fig. 3 is a photograph of the overall system as it was used for the initial operation and evaluation of the CsI samples. It shows the essential parts, like the demountable tube (center), the vacuum system (upper left), the control box (upper right) and the CCD camera (lower right).

Contrary to a conventional sealed off display tube, the demountable display tube is connected to a vacuum pump (upper left in Fig. 3) to permit evacuating the tube after a luminescent sample has been placed in the sample holder and the faceplate has been put in place. After evaluation of the sample's luminescent characteristics, the pressure in the tube is slowly increased until normal air pressure is reached in order to permit removal of the faceplate for the exchange of the luminescent sample under test with another one.

It is crucial for the operation and particularly for the lifetime of the electron gun, that care is taken not to expose the thermionic cathode of the electron gun to air during the change of luminescent samples. Exposure to air will drastically reduce the electron emission of the cathode. Such catastrophic reduction of the electron emission of the thermionic cathode can be avoided by filling the electron gun section of the tube with an inert gas such as nitrogen (N_2) during the change of the samples. The hose feeding the nitrogen into the vacuum chamber is visible in the upper left of Fig. 3.

The vacuum system (upper left of Fig. 3) is mainly a turbo-molecular pump, capable of maintaining pressures of 10^{-8} Torr.

The demountable display tube as it is installed in the overall system is seen in the center of Fig. 3 and in Fig. 4, which is a front view. It shows one of the 3" phosphor samples held by the metal rings (which are also seen in Fig. 2). The white ring holds a viton gasket and a 3.5" glass with anti-reflecting coating, "the tube's faceplate" to seal off the tube during and after pump down.

The control box, visible in the upper right of Fig. 3, and in Fig.5, provides the necessary voltages for the display tube. In particular it features

- Display of a 1024 x 768 line monochrome image on the target. The images are test patterns like the SMPTE pattern [5,6,7] and other pertinent test patterns for evaluation of image display systems. These images are stored in a PC, connected to the control box.
- Adjustable anode voltage, focus voltage, image size, image centering, image brightness and image contrast
- Meters for anode voltage and screen current.

Fig. 6 finally is a photograph of the demountable display tube in operation. The tube displays the SMPTE pattern, using one of the CsI samples as the luminescent phosphors.

Fig. 3 shows also in the lower right part the position of the CCD camera and its lens relative to the display tube. Recall that the CCD camera is used to evaluate the images produced by the various phosphor samples placed into the demountable display system. Actually in this Fig. 3, the CCD camera is slightly moved off-axis with respect to the display tube in order to see the display tube. Fig. 7 is a close-up of the CCD camera and the demountable tube. Fig. 8 shows a portion of the SMPTE pattern, displayed by one of the CsI samples and "photographed" by the CCD camera.

Unfortunately substantial delays occurred during the fabrication process. As a result, the Teltron Corporation did not deliver the demountable tube and its electronic control system until the end of May 1998. Afterwards the system was sent to our consultant Donald Quimette at the University of Connecticut for the purpose of interfacing the demountable tube to a vacuum system and placing the whole structure into a mechanical holder. It was delivered to the University of Arizona in the middle of June of 1998. Following the delayed delivery were more delays as the control box with the drive electronics for the demountable tube showed serious deficiencies and needed to be returned to the manufacturer several times. It is now in a state that it can be used for the major part of the planned tests. Several tests have been performed with CsI samples. However the majority of the planned tests will have to be done in the next year, after our request for no-cost time extension by one year has been granted.

2. Evaluation of three CsI samples

Three CsI samples were obtained from our supplier of phosphor samples the University of California at Berkeley. They were 3" in diameter and had a thickness of 10 µm, 20 µm, and 65 µm respectively. Caution is required when reviewing the results: The samples were acquired in fall of 1998 when it appeared that the Teltron display system was ready for tests. However this was not the case and the samples were stored in our lab under less than ideal ambient conditions for at least 8 months and could have deteriorated during this time. Nevertheless, the University of California at Berkeley suggested going ahead with the tests since they would provide much valuable information. They also agreed to prepare a new set of samples now, since the system is working.

a. Relation between beam current and screen luminance

Of particular interest in evaluating any phosphor sample ("screen") for use in a cathode ray tube is the sensitivity, the relation between beam current and screen luminance. This was done by presenting uniform images (the whole field set to the same digital value), and measuring the luminance with a photometer. The value of the beam current was read with the aid of the amperemeter provided in the control box (see the right red display in Fig. 5). Fig. 9 presents this relation for the three CsI samples in comparison with that of the sealed off tube (shown in Fig. 2) and an experimental screen using a P1 phosphor, provided by Teltron Inc. on a 3" glass plate (identified in Fig. 9 as "Phos-Plate, Alum-back"). Notice that for cases, the relation between luminance and beam current is a linear one. The sealed off tube has the highest sensitivity: for a beam current of about 12 µA, the luminance is about 400 candles/m^2 (candelas per square meter) or 116 ft-L ("foot-Lambert"). With respect to the 3 CsI samples, the sensitivity appears to be proportional to the thickness: the 65 μm has the highest light output: for a beam current of about 12 μA, the luminance is about 160 candles/m^2. This values is clearly lower than that of the sealed off tube, and the CsI samples did not have an Al backing, which all phosphors in sealed off tubes have and which increases the light output by a factor of 2.

b. Relation between anode voltage and screen luminance

Fig. 10 a through 10 c present plots of sample luminance as a function of anode voltage for voltages from 7 to 11 kV with the digital driving signals (the mean GL in the images) as a parameter. Fig 10 a is for the 10 μm thick sample, Fig 10 b is for the 20 μm thick sample and Fig 10 c is for the 65 μm thick sample. Notice that for all samples the relation between anode voltage and screen luminance is a non-linear one: the luminance seems to be proportional to the anode voltage to the power of about 2.5

$$L = a\,(V)^{2.5} + b \qquad (1)$$

c. Modulation of luminance pattern when the sample is excited with a squarewave pattern

In an attempt to get a first idea of contrast transfer, a horizontal square wave pattern of 4 lines on – 4 lines off was written onto the samples. The CCD camera imaged the resulting image and the CCD image was then analyzed using our image analysis software (which was developed in-house). Of interest was the modulation, defined as

$$M = (\max - \min)/(\max + \min) \qquad (2)$$

Fig. 11 shows the results for the 10 μm thick and the 65 μm thick samples. The salient feature seems to be that for the 10 μm thick sample the modulation is much higher than that for the 65 μm thick sample.

d. Beam current as a function of time after placing the command "beam on"

During the experiments it was noticed that at times it took the beam current some time to reach its final value as if there existed a certain "rise time". Therefore we evaluated this phenomenon and plotted the result in Fig. 12. Notice that it took almost 6 to 7 min to reach an equilibrium value. It was never clear if this observation was related to the CsI samples, or if this was a problem with the electron gun in the demountable tube.

III Conclusion

The experimental equipment necessary to investigate the novel cathodoluminescent samples has been developed and is ready to go. Some tests have been performed with three CsI samples. The results are encouraging but by no means conclusive. Since the development and completion of the equipment was extremely late, a request for no-cost time extension by one year is being made such that the majority of the planned tests can be completed.

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[7] Lisk, K.G. SMPTE Test Pattern for Certification of Medical Diagnostic Display Devices. Proc. SPIE 1984;486:79-82.

V. Figures

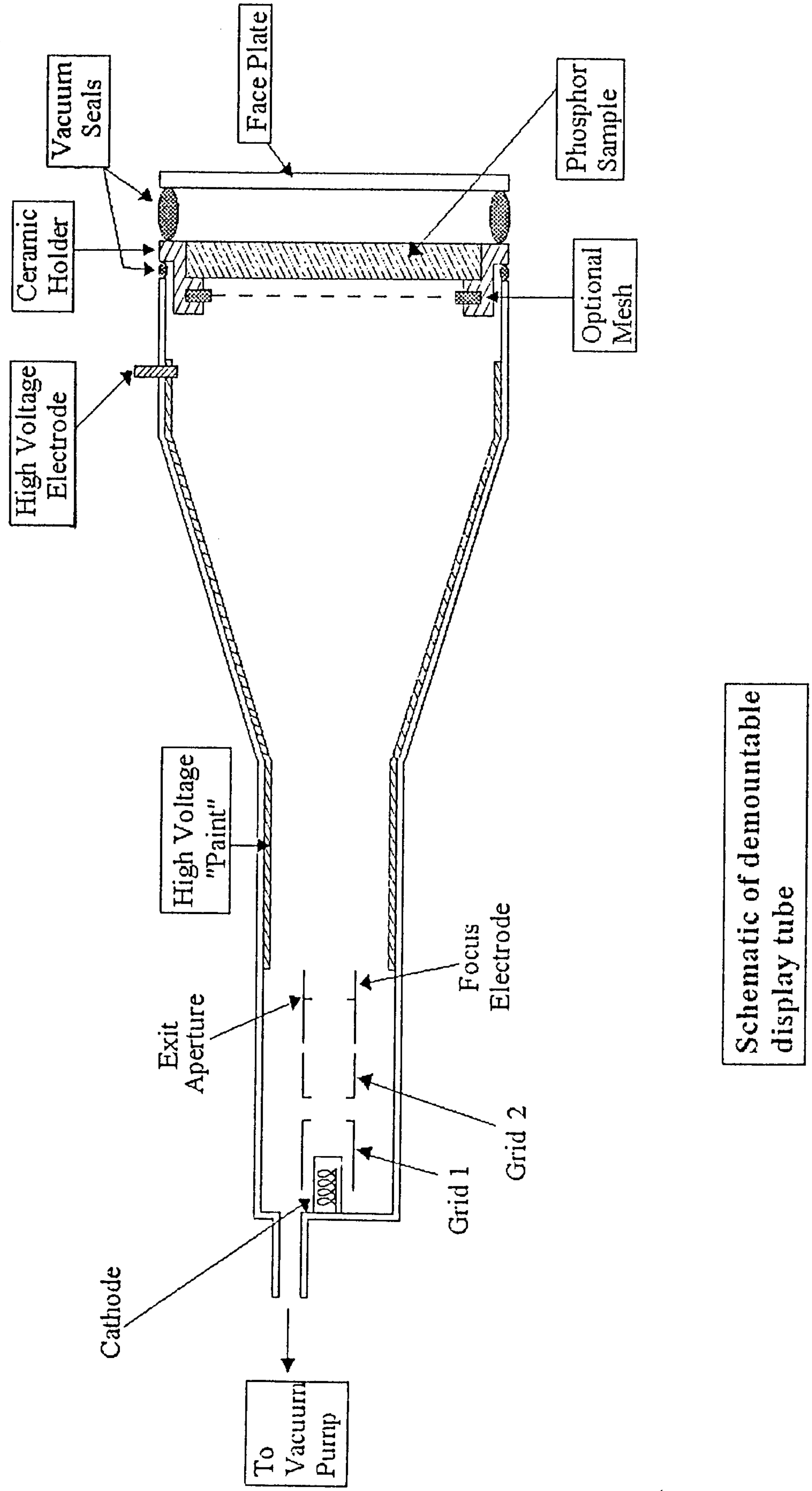

Fig. 1: Schematic of demountable display tube

Fig. 2 Sealed off tube, demountable tube, mounting rings for phosphor samples and two CsI samples in plastic enclosure

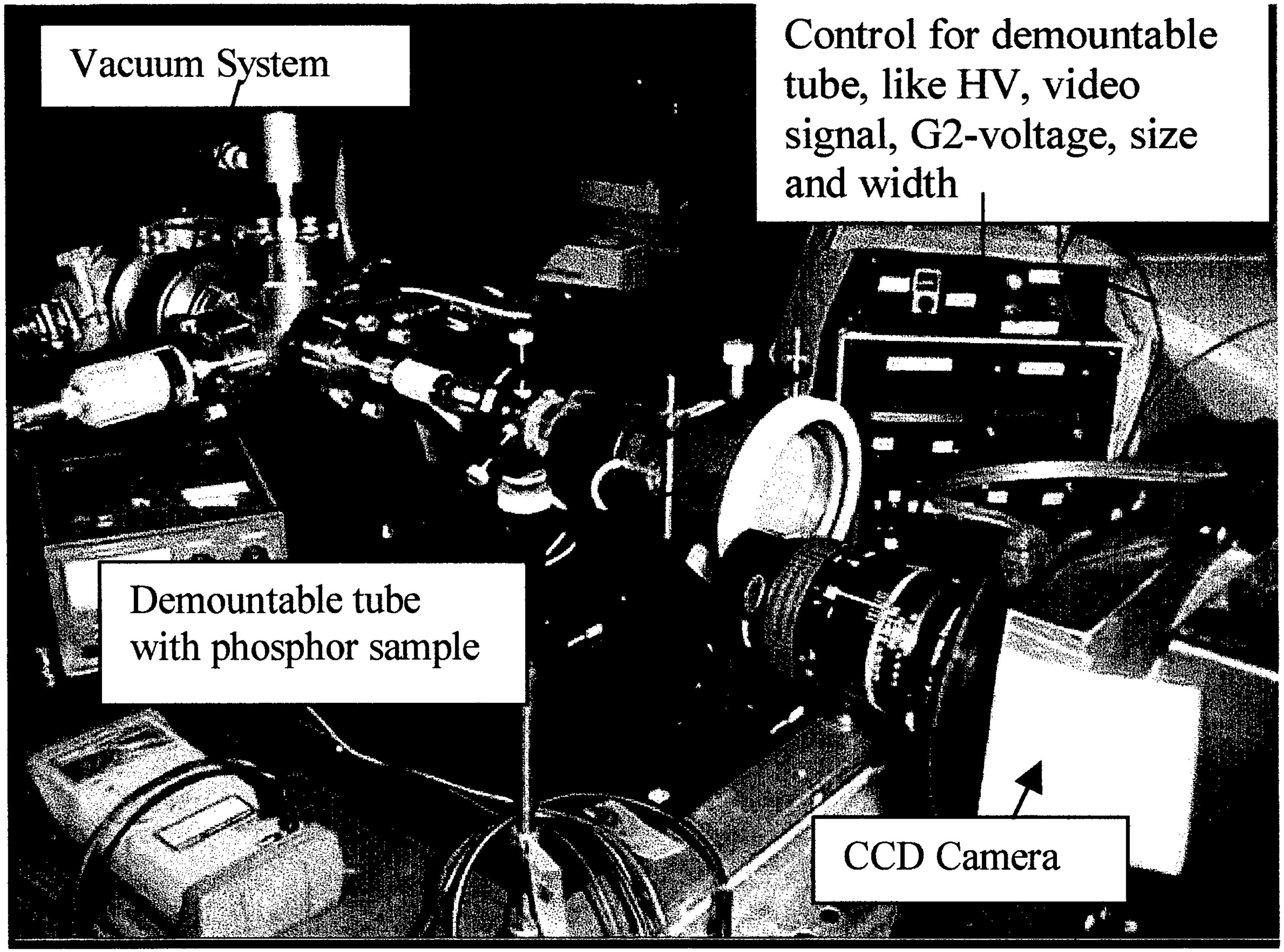

Fig. 3 Photograph of entire demountable system

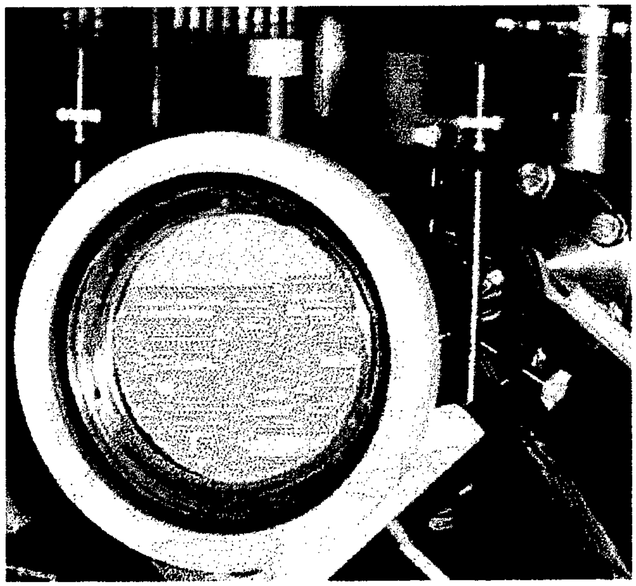

Fig. 4 Front view of demountable tube with a phosphor sample in place

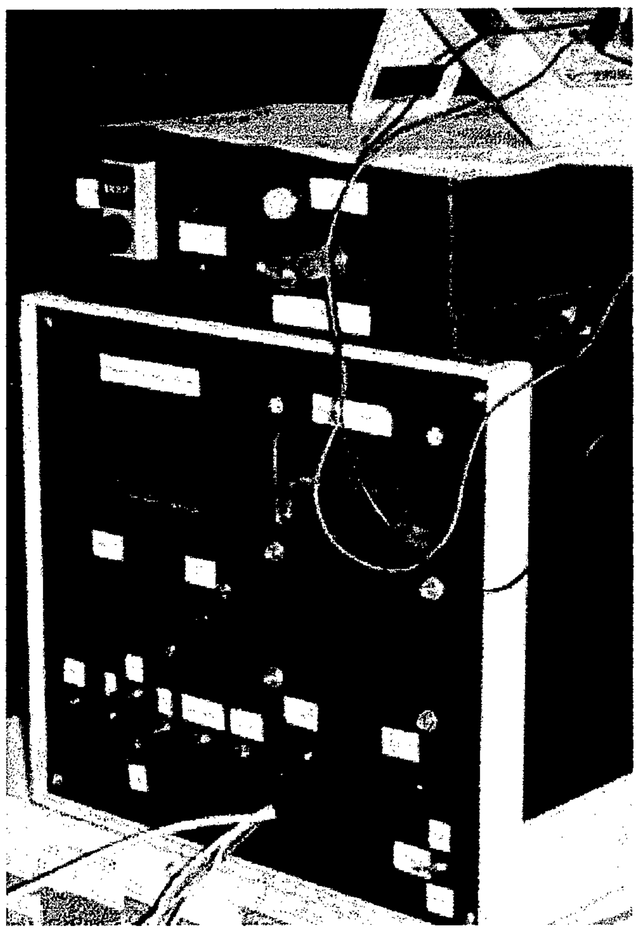

Fig. 5 The control box, providing tube voltages, video signals and meters to monitor current and voltages

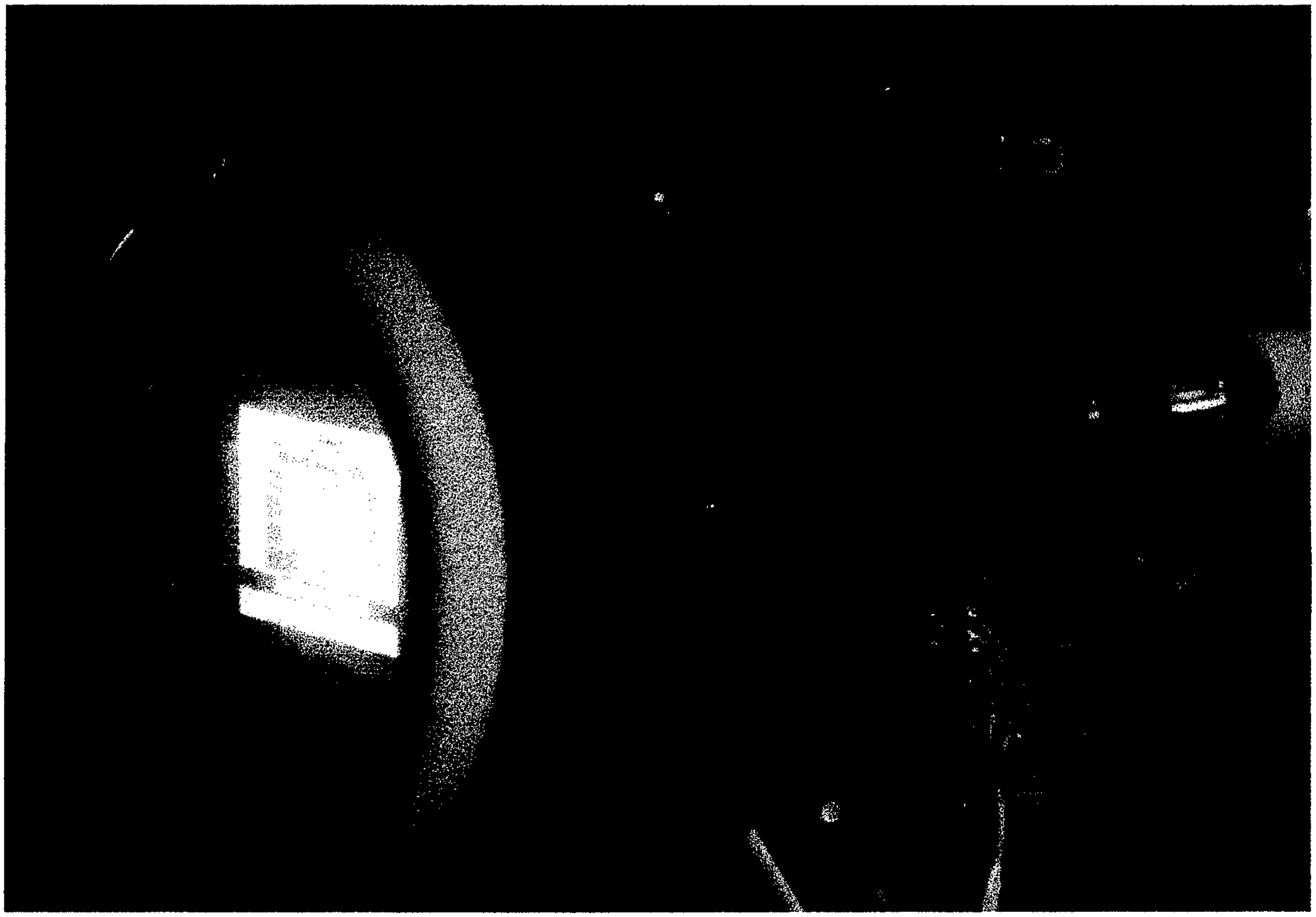

Fig. 6 Demountable display tube in operation. The sample used is one of the CsI samples.

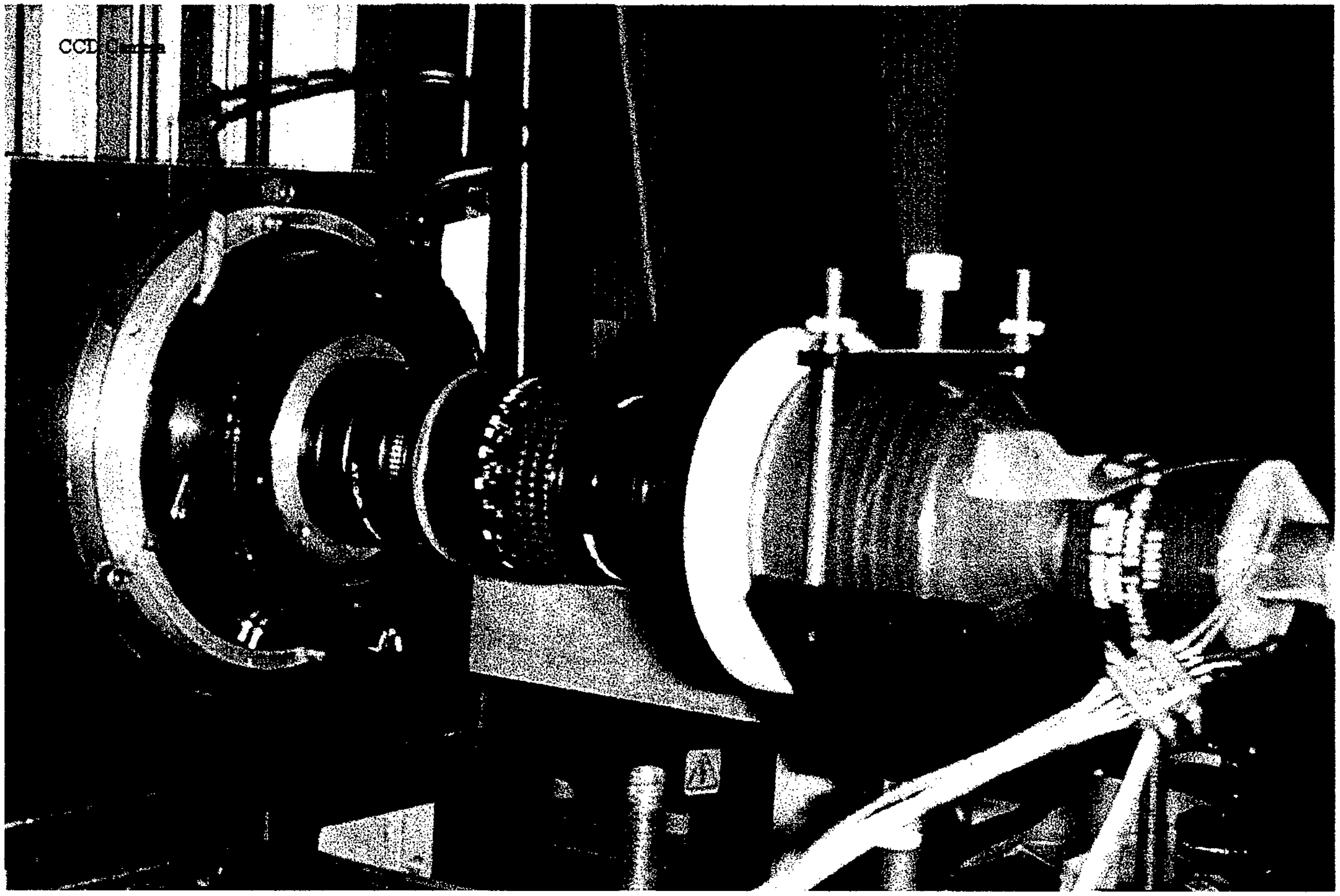

Fig. 7 Close-up of demountable tube and the CCD camera

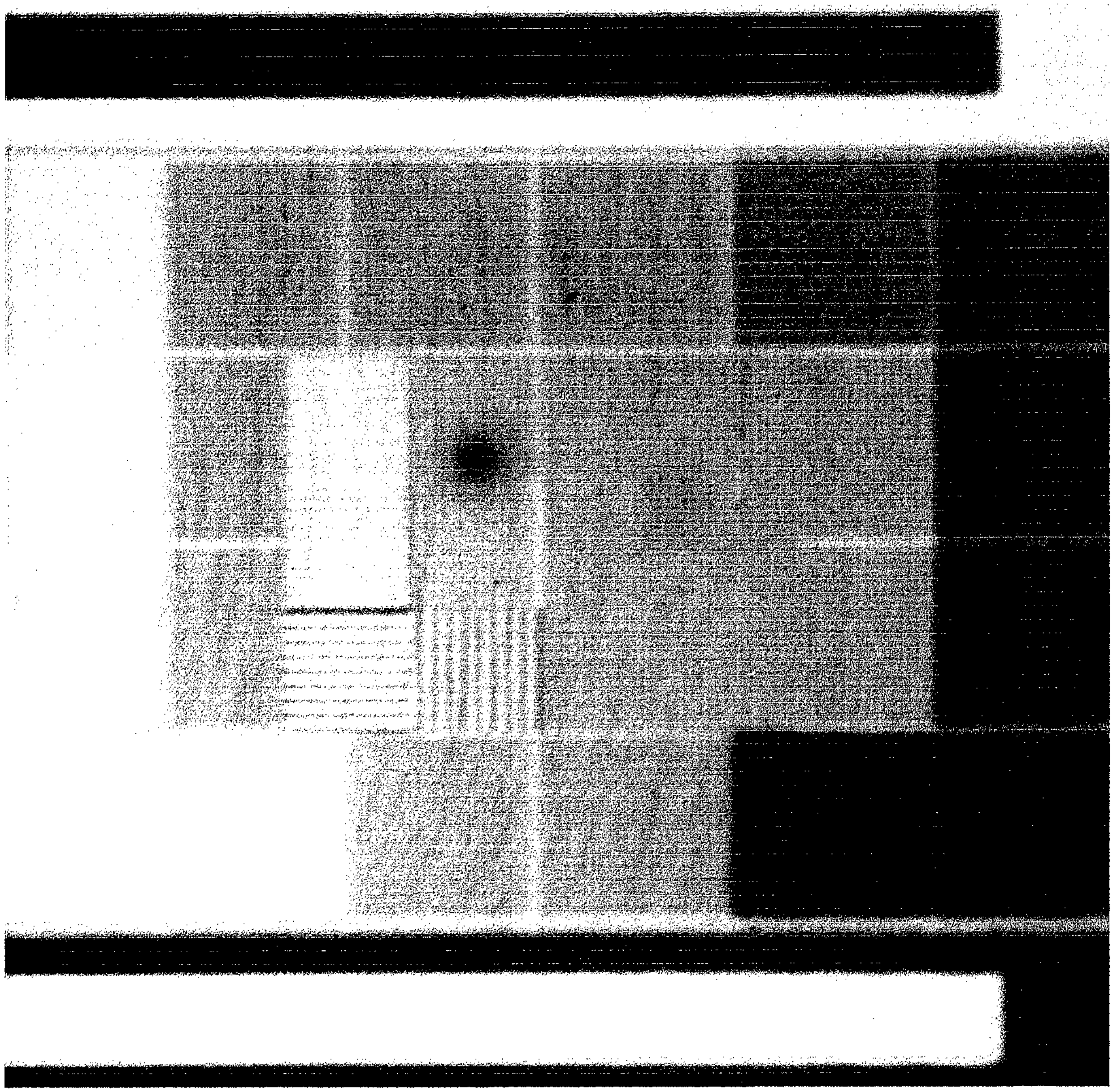

Fig. 8 CCD camera image of SMPTE pattern displayed by the 65 μm thick CsI sample in the demountable display tube

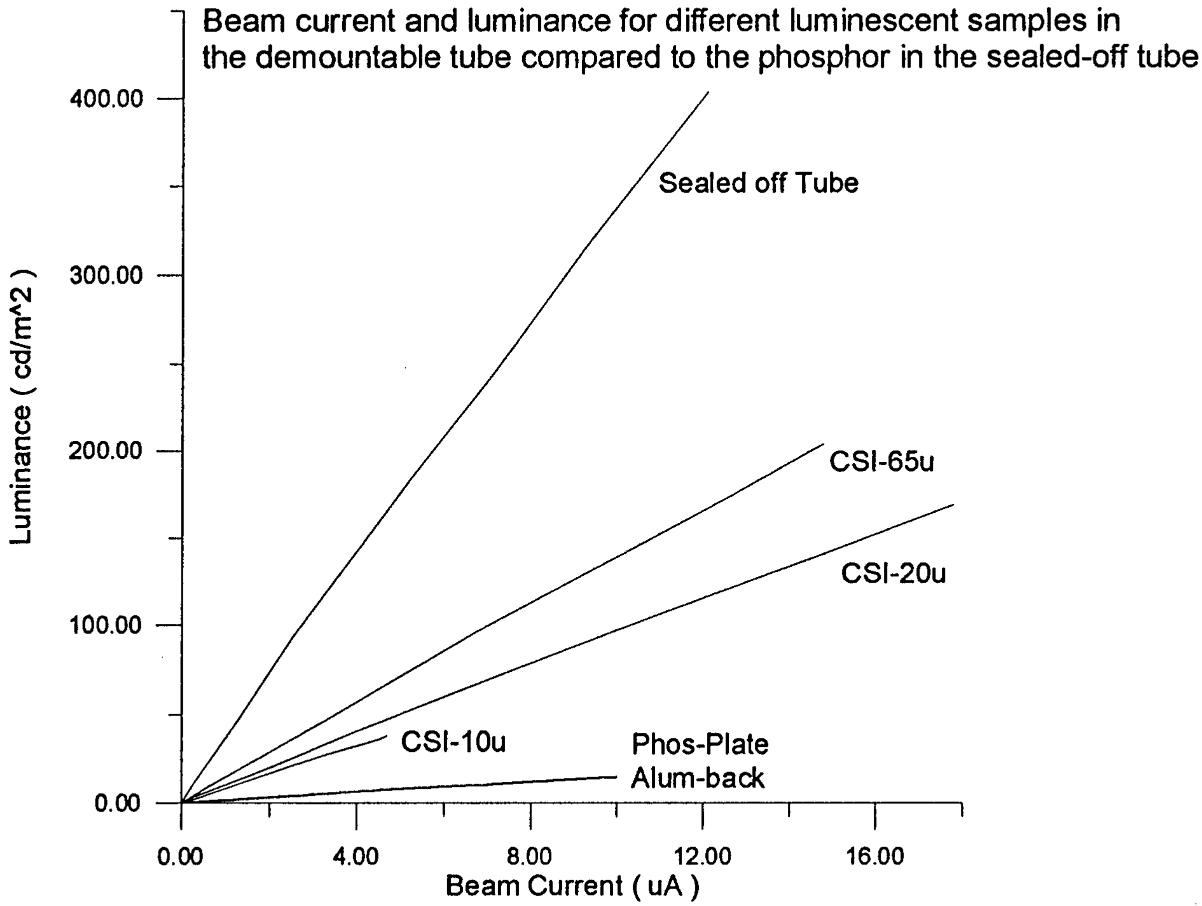

Fig. 9. Beam current and screen luminance for different samples placed in the demountable display tube compared to beam current and screen luminance for the sealed off tube

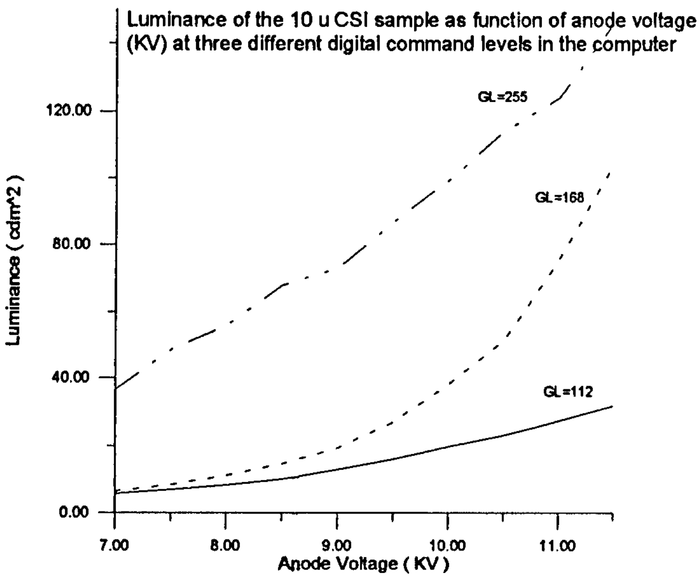

Fig. 10 a Luminance and anode voltage for 10 μm thick CsI sample

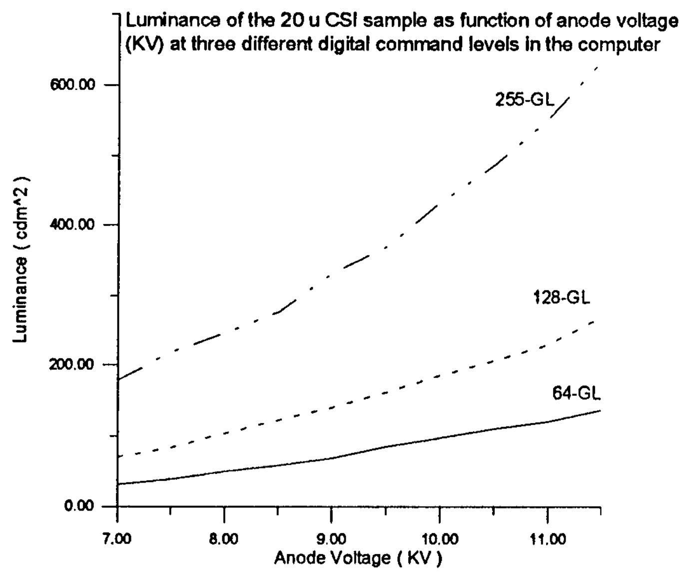

Fig. 10 b Luminance and anode voltage for 20 μm thick CsI sample

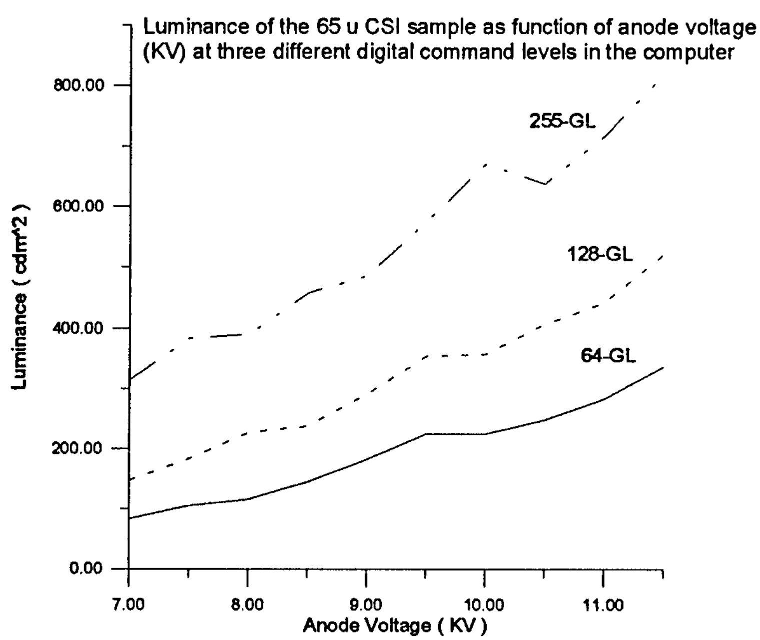

Fig. 10 b Luminance and anode voltage for 65 μm thick CsI sample

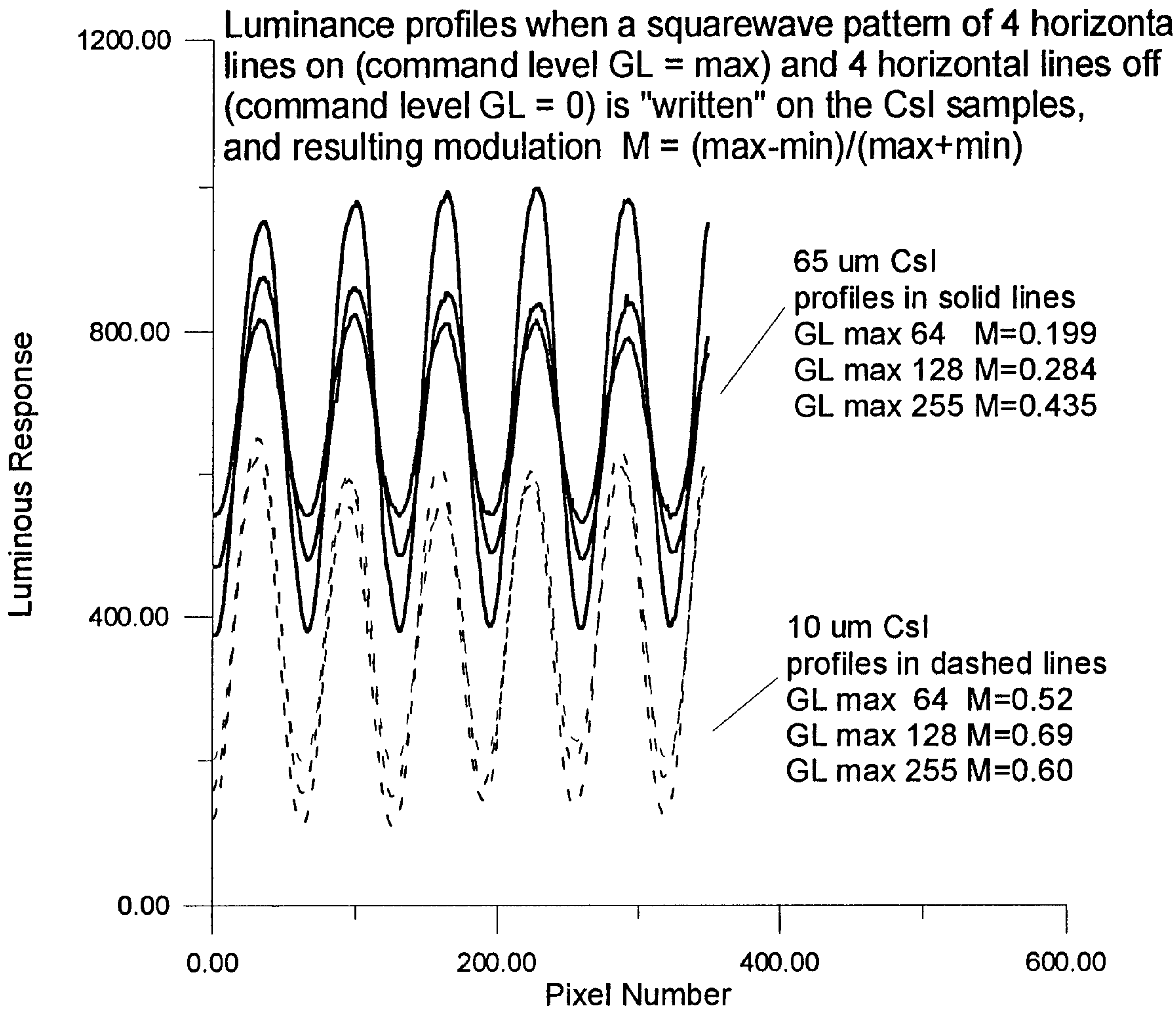

Fig. 11. Luminance profiles and output modulation for the for the 10 μm thick CsI Sample and for the 65 μm thick CsI sample when square wave patterns of 4 pixels on and 4 pixels off at 100 % modulation are written on to the CsI samples

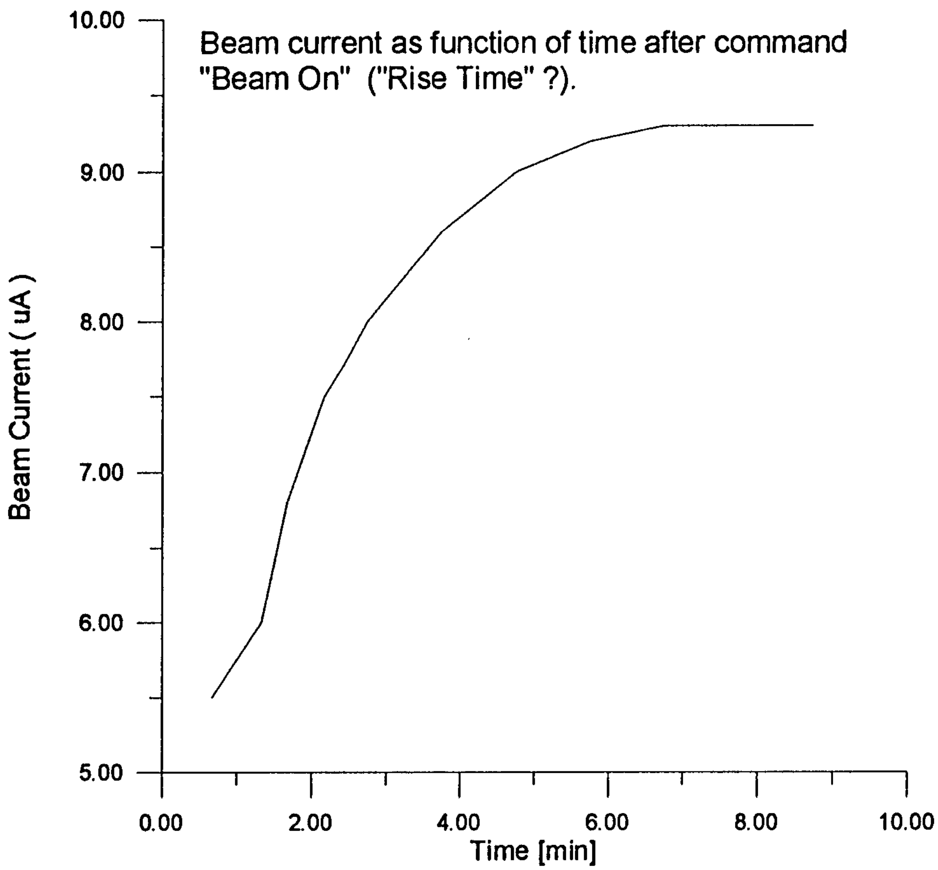

Fig. 12. Beam current as function of time after placing the command "Beam On".

Appendix A

Enhanced Cathodoluminescence With Columnar Type Electroluminescence

by S. Nudelman

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INTRODUCTION:

Our current research program is to pursue the development of a columnar-fiber like type of phosphor to develop into a superior cathodoluminescent material. It originally concentrated on a complete departure from the "State of the Art" by making use of a cathodoluminescent (CL) substance deposited on a substrate in the form of a relatively long thin columnar type of fibers with the fibers oriented perpendicularly to the substrate and microscopically separated from one another. This separation between column-fibers provided the means to gain spatial and contrast resolution heretofore not possible This approach is distinctly different than the 1) conventional phosphor particles deposited on a faceplate as a layer in a binder; and 2) uniform thin film of a cathodoluminescent substance. It explores the relative advantages of depositing the fibrous cathodoluminescent layer on three different substrates. These comprise the conventional glass faceplate, the fiber optics faceplate, and a high definition mesh type shadow mask (15-20 lp/mm). The latter will be separated from the faceplate.

Professor Nudelman undertook an extension of the originally proposed research into what other means could be conceived for enhancing the performance of these columnar type phosphors into directions that could lead to markedly enhanced brightness while maintaining the original goals of improved spatial and contrast resolution. The new conception is based on applying an intense electric field along the length of the fiber by applying a difference of potential across its length. This has the impact of generating electroluminescence along the length of the fiber with two advantages. First, the electroluminescence is to be governed by the video signal. Second, the brightness of the light output is to be the sum of cathodoluminescence generated at the columns input plus the electroluminescence generated along the columns length. This columnar approach is completely different than attempted heretofore in that it makes use of a mechanism combining electron injection with collision excitation. Furthermore, the injection is not across a p-n junction but from electron beam penetration into the host lattice.

The study proved to be extensive and included application to FED, CRT and projection types of displays. It is designed to increase the light output from the columnar type of phosphor layer through the simultaneous application of the electron beam and an intense electric field. This combination is designed to generate not only cathodoluminescence within 1-3 microns at the input end of the column impacted by the electron beam, but in addition video controlled, bright electroluminescence throughout its remaining long length for gain and light enhancement. It should be stressed that electroluminescence with **thick** crystalline columnar phosphor layers is completely different than those developed over the past 50 years, i.e., phosphors powders in a binder or thin films. It represents a new direction aimed at overcoming present limitations in electroluminescence, as well as supporting the advancement CRT and FED types of displays.

Cathodoluminescence Plus Electroluminescence

BACKGROUND:

Electron beams have been used in the past with electroluminescence, but for an entirely different purpose. They have addressed the problem of electron beam switching of AC operated electroluminescent phosphors with memory as used in storage display tubes[1-3].

Electroluminescence was first observed by Destriau using powder ZnS phosphors suspended in an oil, 1936[4,5]. His research was delayed during the war years, but reemerged after the war with the powders embedded in a binder. Over the past 60 years, intensive research has been carried out in laboratories of the government and industry to measure and improve performance. Many different designs have been attempted which include the use of electroluminescent powders in a binder, thin films, with and without dielectrics, and operating with AC as well as DC. As noted by Anton, "all of these different phosphor layers depend upon the use of high fields to accelerate free carriers so that their energy is sufficient to generate additional carriers by impact ionization of the host ions and to directly excite some of the activator atoms such as Mn and Tb"[6]. Anton also reports, "The electron once it is in a conduction band state, can rapidly accelerate to kinetic energies of the order of $(3/2)E_g(\sim 5.4$ eV) which is required to efficiently create secondary electron-hole pairs by impact ionization (from Gunn[7]). "These high fields can occur across the entire layer (most likely in the case of thin film devices) or localized at grain surface heterojunctions, as in the case of powder EL devices(see Alder et al., 1981)"[8].

An excellent review of electroluminescence has been provided by L.E. Tannas, Jr. in a chapter on Electroluminescent Displays which appears in a book titled "Flat Panel Displays and CRTs"[9]. Special note is made of it here since it covers in a very complete manner, the theory, operation, fabrication, and status of AC and DC electroluminescent structures. There is little need in this study to provide an in depth review of the subject. Thus, it is highly recommended reading. It is very complete, excepting at that time, the Field Effect Display was in its infancy, and has since emerged as a contender for future primacy as a flat panel display. In addition, there are other important reference books that serve as an excellent background which help understand the basis for this study, namely "Luminescence of Inorganic Solids" and Electroluminescence Materials, Devices and Large Screen Displays".[10,11]

More recently, a detailed study of flat panel display technology in Japan, Russia, Ukraine and Belarus was undertaken by Tannas et al.[12] It was interesting to note that the Japanese have essentially settled on LCD displays for most future applications with electroluminescence being relegated to custom tasks. In their opinion, "the brightness of a blue phosphor must be improved by a factor of 5 or 6 before the electroluminescence technology can become viable." Overcoming this limitation is one of the aims of this research study, i.e., generating bright blue electroluminescence.

PRELIMINARY STUDIES

This research study replaces the conventional phosphor powder embedded in a binder with a columnar type layer to serve as the cathodoluminescent layer in CRTs and FEDs (Field Effect Displays). These columns grow from the substrate in a perpendicular manner, as demonstrated by CsI in Figure 1, and described in detail by Goodman[13]. This kind of layer is used in X-ray image intensifiers with CsI functioning as an X-ray absorber that emits light in response to the intensity of the X-rays. In this application, the CsI columnar layer replaced the traditional layer of CDs powder in a binder used in the early X-ray image intensifiers. It was designed to provide reduced scatter, improved spatial resolution, and contrast in X-ray images, and was eminently successful. We anticipate similar benefits when this structure is used in displays.

The second procedure is not only to train a high energy beam of electrons onto this columnar type of phosphor surface as in the typical CRT, but to simultaneously apply an electric field across this columnar layer. The electric field is needed to generate video controlled electroluminescence in properly designed phosphor materials.

AC operated electroluminescence panels use the simple structure shown in Fig. 2. It comprises a simple condenser like electrical sandwich, i.e., an electroluminescent powder layer embedded in a binder between two electrodes. The substrate is glass whose interior surface is coated with a transparent conducting electrode. The phosphor layer is deposited on the transparent electrode. The back surface of the layer is coated with an opaque electrode such as evaporated aluminum. Thus, it is a simple matter to apply a voltage source to the electrodes and establish an intense internal electric field sufficient to cause electroluminescence. We show an AC source in Figure 2 since phosphors embedded in binders require AC for their operation. However, DC electroluminescent phosphors not needing binders have been created that can be operated with DC and voltage pulses, so that the nature of the voltage source can be whatever the selected phosphor requires.

Tannas describes the three major mechanisms used to achieve emission from electroluminescent materials[9]. They are:

"Type 1: Bipolar alternating double-injection luminescence, demonstrable with AC powder $ZnS:Cu_xS$ phosphors, or the Fisher model.

Type 2: Hot electron impact ionization of activator demonstrable with AC thin film ZnS:Mn and DC powder $ZnS:Cu_xS$ phosphors or the Chen and Krupka model.

Type 3: Memory effect in AC thin film ZnS:Mn phosphors first reported by Yamauchi et al (1974) and described by Onton and Marello."

The electroluminescent approach described makes use of Type 2 impact ionization of activators and resembles the DC thin film electroluminescence display. It does not require the double injection process of Type 1, nor does it require the memory effect of Type 3. However, it does make use of a video controlled single injection process that has not been explored heretofore. This approach with

DC is simple to understand and to implement in a straightforward manner. It offers uniform electroluminescence along a column versus the comets of Type 1 and the filaments of Type 3. Tannas points out in regard to DC film displays: "The thin films of phosphor at high fields tend to suddenly spark and catastrophically break down." Our columnar structure-layer represents a thick film rather than a thin film and should not be prone to catastrophic breakdown. They are expected to be 5 to 100 microns thick, corresponding to a column length selected for the application, compared to 1-3 micron thin films.

A Hypothesis: Cathodoluminescence enhanced by electroluminescence is based in large part on the following sequence of events. First, the incident beam electrons cause not only cathodoluminescence, but also the generation of a population of electron-hole pairs. Second, the simultaneous, continuous application of an electric field causes the electrons and holes to immediately drift in opposite directions. Third, the holes drift toward the adjacent aluminum electrode through which the beam electrons must pass, whilst the internal electrons drift through the column toward the high voltage, transparent conducting electrode. Fourth, the electrons gain sufficient energy to cause impact electroluminescence of activators such as manganese, or even band gap transitions, as required. Consider the single columnar structure shown in Figure 3. The high energy beam electrons strike the end of the phosphor column after passing through the aluminum layer. They generally penetrate the column a distance of 1-3 microns depending upon electron energy needed to excite the desired brightness of cathodoluminescence. Simultaneously these electrons create a profuse concentration of electron-hole pairs at the input end of the phosphor column. In the process, the beam electrons become thermalized as do the electrons from the electron-hole pairs. The electric field then causes the holes to drift instantaneously toward the adjacent aluminum electrode whilst the electrons drift in the opposite direction toward the high voltage, transparent electrode expected to be 5 to 100 microns away, depending upon the length of the column. The field then accelerates these electrons to sufficient energies to cause impact excitation of electroluminescence. The separation of the electrons and holes provides an effective electron lifetime that is sufficiently long for electrons moving through a column to achieve sufficiently high energies repetitively, and cause electroluminescence throughout the column length by impact excitation with activators and host ions. Note that for the purpose of generating gain with electroluminescence along the fiber, it is only necessary to inject the electrons and not necessary to have cathodoluminescence.

Sahni notes that an electron which enters the ZnS lattice with an energy of 10,000 Volts will generate 1000 electron hole pairs[3]. Normally, these electrons and holes have nowhere to go in a CRT and simply recombine primarily through cathodoluminescence, and radiationless, non-visible transitions. However, with the simultaneous application of an electric field, the electrons and holes are immediately separated by drifting in opposite directions. It is possible to generate a rough estimate of the light output from this excitation process. The electrons are accelerated and can gain significant energy in a very short distance for impact excitation processes, such as from bandgap, donor-acceptor, and/or activator centers transitions.

Consider the Mn activator in ZnS which requires 2.5 eV for excitation. We conservatively estimate that it requires twice as much energy from the electrons to excite the Mn atom to luminescence along the length of the column , i.e., 5 eV per exitation. An electron in a field of 10^6 eV/cm acquires 5 eV in 500Angstroms. Thus, after exciting a Mn atom to luminescence, the electron is again thermalized and can be accelerated every 500 Angstroms to excite additional Mn atoms along a column. If the column is 10 microns long, each electron has as much as 200 opportunities to strike a Mn atom with sufficient energy to excite electroluminescence. If the column is 100 microns long, there will be 2000 opportunities per column per electron to generate electroluminescence from Mn. Thus, we can anticipate as much as 200 to 2000 excitations to occur along the column. If a beam electron had 10,000 Volts of energy entering the ZnS column and created 1000 electron hole pairs, then each beam electron could be responsible for 200,000 to 2,000,000 opportunities to generate light in its passage through the column. This is a remarkably favorable result. The actual number of photons emerging should be specified in terms of electroluminescence efficiency. Many factors effect that efficiency such as the concentration of activator centers plus light lost through the cylindrical wall and ends of the column as well as the magnitude of deleterious trapping.

If we accept a very poor efficiency of 1% to allow for trapping as in powder phosphors, the number of effective excitations reduces to the range of 2,000 to 20,000 per beam electron, which is still an extraordinarily favorable result.

These numbers should be compared with the light output from a "state of the art" CRT.
The brightness from such a CRT is generally falls in the range of 100-140 foot lamberts. **This analysis suggests that the brightness could be increased by a gain factor of 2,000 or more.** This is tremendous overkill. Fortunately, gain is controllable simply by reducing the beam current, and/or the bias voltage across the columnar layer, e.g., 10^5 Volts/cm. Much lower gains is required for displays, but is highly attractive for video projectors.

The electronic speed of response should be excellent and depend primarily upon the electroluminescent decay time.. The electron mobility for electrons in ZnS is a very modest 180 cm^2/(Volt sec). Even with this low mobility, an electron gains sufficient energy within 10^{-13} to 10^{-14} sec to generate electroluminescence per 500A. Thus the time to move through a 100 micron column remains only a fraction of a nanosecond

It is reasonable to estimate the number of excitations caused by a beam electron in generating **cathodoluminescence.** If we use the same approximations as above for the electron energy, i.e., 10,000 Volts of energy for the electron penetrating the column and 5.0 eV to excite Mn to luminescence, then there could be as many as 2,000 excitations for cathodoluminescence. If we assume that the cathodoluminescence efficiency of ZnS is a realistic 10%, the effective number of excitations reduces to about 200. This number should be compared with the 2,000 to 20,000 opportunities to generate only 1% efficiency in electroluminescence derived above for the electroluminescence columns. Clearly, there is every reason to believe that the electroluminescence generated along a column can be expected to certainly equal, but most likely, greatly exceed that generated by the original beam electron's cathodoluminescence. Notice that the electric field can be an order of magnitude smaller and still contribute significant, desired electroluminescence. Clearly, a substantial increase in the light output can be expected from CRTs and FEDs that are designed to make use of cathodoluminescent phosphors able to be stimulated to electroluminescence by injected beam electrons when combined with an applied electric field.

Substantial contrast enhancement can be derived from this kind of gain as an additional befit. It can eliminates the need for the reflecting aluminum layer which currently provides an optical gain factor of about 2 in brightness. The controllable gain expected from the above analysis, which could be as much as 2000 or more, far exceeds the factor of 2 and permits the replacement of the aluminum reflecting layer with the deposition of an opaque, light absorbing conducting black layer. This arrangement reduces the problem of ambient light as well as that generated within a column in the direction of the aluminum layer and reflected forward into other adjacent columns.

It is important to stress that the amount of electroluminescence generated is dependent upon the video signal carried by the beam current. Since the intensity of electroluminescence starts with the beam's injected electron, it follows that the more beam current, the more electrons injected, and the greater will be the electroluminescence; and vice versa for less beam current. It should also be stressed that this approach requires avoiding the use of conventional electroluminescent phosphors. We do not want the field strength to turn on conventional electroluminescence that is in any way independent of the beam electrons carrying the video signal. Any such electroluminescence would clearly cause an unacceptable loss of contrast.

Pursuing a more accurate estimate of the electrons lost through factors such as radiationless transitions and trapping is premature, since this column structure has never been explored before for phosphors. An accurate estimate of the injected electrons available for generating electroluminescence requires a Monte Carlo calculation based on acquiring reliable experimental data pertaining to column phosphors.

Another point raised by Tannas is: "the main attraction of DC thin-film electroluminescence has been its relatively low operating voltage and its simplicity. However, the construction is perhaps more difficult than AC thin-film electroluminescence because of the requirement for isolating the phosphor at each row line or each pixel."[9] Since our application is with the CRT and the FED and uses beam electron injection, there is no need for the electrical pixel isolation as required in a flat panel row-column matrix. This permits coating the layer fully with an electrically conducting layer as needed for an electron beam generated display.

Our attraction to columns is stressed in the current research contract. It is worthwhile to repeat the basis for that orientation here, namely important optical considerations. By using free standing columns, i.e., not touching one another, we derive several important benefits. Channeling of the light along a column occurs resembling loosely a fiber optic and a substantial reduction in the light lost from penetrating out the sides (compared to a thin film). For example, ZnS has a refractive index of 2.36. If a spot of electroluminescent light is created in the center of the column anywhere along its length, the amount of light escaping out the wall of the column is given by equation 1[14].

$$F = \frac{1}{4}\left(\frac{n_2}{n_1}\right)^2 \left[1 - \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \right]$$

where n_1 and n_2 are the index of refractions for the two media.

Substituting the index of refraction n_1 for ZnS and n_2 for air leads to only 3.75% of the electroluminescent light escaping through the column wall. Note that only one half of the escaping light is in the forward direction, i.e., toward the faceplate. This is enormously favorable compared to that scattered by a phosphor powder layer or light lost through a thin films multiple internal reflections. In addition, when the electron beam strikes the end of the phosphor column after passing through the aluminum electrode, it generates light within 1-2 microns of the surface. Thus, the amount of light lost is somewhat less than the 3.75% noted above, since the aluminum layer will reflect light back into the column. If this escaping light still proves significant, particularly in causing some loss of contrast resolution, it could lead to another aspect of subsequent materials research, i.e., to fill in the voids between the columns, or to coat the columns with; 1) an insulating absorber to capture any escaping radiation or 2) a dielectric reflector to confine the light to each column.

The matrix addressability problems described by Tannas apply when the addressability is at the phosphor layer. In the cases of the CRT and FED, addressability is provided by control of the electron beam.

There are other considerations that apply to our structure. Ideally, the only electrons injected into columns are from the electron beam. This is most important since only in this way can the generated electroluminescence be controlled by the video signal. Thus, it is very important that there be little to no injection of electrons from the beam side electrode. The electrode phosphor column interface should be ohmic or it should provide an effective blocking barrier to electrons from the electrode. For the same reason, the transparent conducting layer should be blocking to holes or ohmic. If the contacts are ohmic there will be a dark current whose magnitude will depend upon the resistance of the columns and the difference of potential between the electrodes. The brightness from the display will depend upon the light generated by the injected beam electrons causing a sum of cathodoluminescence and electroluminescence light output. Any low level background light will be determined by the electrode injected dark current and the level of electroluminescence light output it generates. With blocking contacts, it should be minimal. With ohmic contacts, the columns should be grown from substances offering the greatest resistivity. Fortunately, evaporated ZnS can have a resistivity as high as 10^{13} ohm.cm.

Although, this research is directed to the use of DC thick columnar electoluminescent films, a device with the structure, such as of Figure 3, can be made to operate with AC, with and without memory, with phosphor powders or films. **The concept is based on the injection of beam electrons into a material which can generate electron-hole pairs and thereby initiate electroluminescence with the simultaneous application of an intense electric field.**

When, the material is cathodoluminescent, it offers the opportunity for enhanced light emission and/or color flexibility in color emission. The cathodoluminescence can be of a color difficult to generate with electroluminescence and thereby permit a degree of flexibility in color mixing not possible heretofore. It is also conceivable that an substance capable of electroluminescence based on electron injection, could be coated with a layer of some other substance than a cathodoluminescent phosphor, whose main attribute is the ability to generate a greater concentration of electron-hole pairs under electron bombardment. Thus, with the field biased so that the electrons can be readily injected into the electroluminescent substance, there is no requirement here to generate cathodoluminescence.

Particular Advantages for the FED: This kind of cathodoluminescent gain using field controlled electroluminescence can be particularly beneficial for Field Effect Displays. Such gain could reduce the voltage applied presently across the vacuum space, i.e., needed between the array of emitters and the phosphor layer, to achieve a satisfactory level of brightness. Currently, these high voltage requirements over a small spacing distance are susceptible to a breakdown problem.

The use of a columnar fiber layer makes possible the replacement of the high voltage across the vacuum space of the FED with a high voltage applied across the cathodoluminescent-electroluminescent layer. Here, that applied field generates gain and electroluminescence whose intensity per column is governed by the video signal from the scanning electron beam generated by the matrix of field emitters. The energy required of the injected electrons need only create enough hole-electron pairs so as to meet the gain and brightness requirements of the display. In effect, we are replacing the brightness required from cathodoluminescence with video controlled very bright electroluminescence. The evolution of the FED has been slowed by the desire to develop bright cathodoluminescent phosphors operating at relatively low accelerating potentials, e.g., 1000 Volts. This low voltage cathodoluminescent phosphor development has proven difficult, if not satisfactory, to date. It has led to some manufacturers giving up this approach and using high voltages, such as 10,000 Volts. This was made possible by increasing the separation between the phosphor layer and the field effect emitter structure. The result is a less attractive, thicker flat panel display. As noted above, 1,000 eV electrons injected into the ZnS should create 100 electron-hole pairs. Assume again, e.g., a long Mn doped column of 100 microns with 10,000 Volts across the column and a conservative 5 eV required for excitation of the Mn activator. Following the same analysis as above, leads to 100 electron-hole pairs for a 1000 Volt electron, 200 opportunities for excitation per electron along the length of the column, and 20,000 opportunities to generate electroluminescent light output from the 100 electrons generated by the impacting 1000 Volt electron. In this approach the net voltage is reduced to the 1-3 keV required to pass through the aluminum electrode plus the 1,000 Volts required for electroluminecence. Note a point to be stressed. If the gain is sufficient, and reflected light from the aluminum electrode is not necessary, it can be replaced by an opaque or transparent electrode requiring less energy to penetrate the electrode, perhaps only hundreds of volts versus thousands of volts.

It is important to emphasize that the scheme describe above for the FED display replaces the high voltage of 10,000 eV between the cathodoluminescent phosphor and the Spindt pixel array of emitters, with only 2,000 to 4,000 Volts. The 10,000 Volts now is across the electroluminescent layer and is not across the vacuum space. It substantially reduces if not eliminates the high field strength breakdown problem faced by FEDs heretofore. Thus, by using the beam only to create a population of video controlled electrons for electroluminescence imagery, we can seek to obtain the brightness desired with FED high beam currents and without the high voltage-field detriment required for achieving bright cathodoluminescence.

Other Attributes for CRTs and FEDs: Consider Figure 3 which illustrates the mechanism for charge injection as a prerequisite to electroluminescence. A simple two color emitter can be made from this column. The initial deposition of a ZnS column could be activated so as to generate bright blue cathodo-electro-luminescence.
During the growth of the column, it is possible to add an activator such as manganese optimized for cathodoluminescence. In that way, a reddish-yellow cathodoluminescence is generated by the beam electrons whilst blue electroluminescence is generated near the faceplate end of the column. Since the electric field could be controlled by changing the applied voltage, i.e., from fully on to fully off, the light emerging from the column could be changed from simply the cathodoluminescence reddish-yellow to its sum with the the voltage controlled electroluminescence blue. It follows that one can anticipate changing activators with column growth so that 2 or more electroluminescent colors can be generated. Thus, e.g., by properly adding activators along a columns length, it also offers the potential for creating a white luminescence or any subtle color as required for an application. A boundary condition, however, is that the order of activator additions does not impose attenuation factors that could absorb colors generated at the input end of a fiber before they could emerge from a column at the transparent faceplate.

It is also reasonable to alter the growth of a column so that one might start with one phosphor and change to another. The same logic applies here as above in that the selection of the different phosphors along a column does not attenuate the light from the aluminum electrode end emerging from the faceplate end. For example, it might be desirable to start with CDs for electroluminescent green emission and add the red emission from CdSe for cathodoluminescence. Other examples include ZnS blending into ZnSe or ZnS into CDs, or vice versa. It is important to note that the experimental procedure of Goodwin does not depend upon the usual matching of crystal structure, since the technique for overgrowth is primarily a mechanical process[13].

An Experimental Method: In order to combine cathodoluminescence with electroluminescence, it is necessary to build the equivalent of the simple electroluminescent panel shown in Figure 2, into the phosphor end of a demountable CRT, as in Figure 4. There is shown a CRT with its electron gun at the rear. The front of the tube has a demountable faceplate. Inside there is room for the insertion of a disc serving as the substrate for the columnar type cathodoluminescent layer. Both sides of the disc are coated with a transparent, electrically conducting layer. The rim is also coated with a conducting material so that the front and rear surfaces have an electrically conducting path from front to back. The columnar phosphor layer is deposited on the conducting surface of the disc facing the electron gun. The exposed columnar layer surface is coated with a thin aluminum film, thick enough to permit the penetration of beam electrons with relatively small amount of energy loss, (i.e., 1-3 keV), but thick enough to provide good conductivity. This loss of energy in the aluminum layer is not a problem for the CRT but it has presented a problem to Field Emission Displays (FED), as noted above. Note that a conductive seating ring at ground potential makes contact with the aluminum film while the opposite phosphor surface is at an elevated, positive potential through contact with the conductive clamping ring. The clamping ring is connected to the voltage source through the electric field electrode. With this experimental arrangement, it is possible to have high energy electrons in the beam pass through the aluminum layer and penetrate into the phosphor to cause cathodoluminescence (in the usual manner). However, in addition, the applied very intense electric field now can accelerate the injected electrons to cause the requisite video controlled electroluminescence.

The transparent electrode can be placed hundreds to thousands of Volts positive relative to the aluminum electrode (depending upon the column length). The voltage source in most cases will be simply DC for our phosphor-columnar layer. It can also be AC as well as pulse trains over a wide range of frequencies. Although stress is placed on the attributes of the columnar layer in this research program, note that this experimental arrangement permits the same tests to be carried out on AC powder cathodoluminescent phosphors deposited in the usual binder. Furthermore, any of the waveforms derivable from good function generators can be used. Prior history with electrophotoluminescence, e.g., illustrates that a variety of effects can result from such fields, such as quenching as well as stimulation of luminescence[15-19]. These fields provide enormous experimental flexibility in understanding basic mechanisms responsible for observed luminescence effects.

Notice that a substantial negative voltage accelerating potential is applied to the cathode end of the tube and the aluminum layer coating the phosphor surface is at ground. This is contrary to the conventional CRT where the aluminum layer is at a positive high voltage. Normally, the aluminum film serves as the last electrode of the electron optics and carries the high energy voltage, generally in the range of 10 to 30 keV. This new scheme makes it simpler to apply the voltage generator for electroluminescence to the phosphor layer since its inner electrode is at ground.

The experiment described above, i.e., cathodoluminescence plus electroluminescence, is an electrical analogue of the light amplifier reported by Cusano in which ultraviolet light illuminated a layer of ZnS:Mn phosphor film[20]. His film was sandwiched between an opaque electrode and a transparent conducting layer on a glass faceplate. A difference of potential across the film led to a visible image with many more photons of light emerging per uv photon input (electro-photo-luminescence [EPL]). Absorption of uv photons caused the excitation of electrons into the conduction band which could be accelerated by the electric field. The explanation for this light amplifier's operation by Williams was based on the assumption of an exhaustion layer at the interface between the ZnS:Mn layer and the negative electrode[21]. This led to a non-uniform distribution of the electric field and a very high localized field of 10^6 Volts/cm.

A significant difference in geometry should be noted between the Cusano light amplifier and our electron beam-electric field amplifier. The Cusano amplifier illuminates the phosphor with a uv image through the glass faceplate and the visible image emerges through the same faceplate surface. Thus the excited electrons are generated mostly at the front surface by the uv and diminish exponentially with depth. In our case, most electrons are generated at the immediate back surface of the film so that the electric field has greatest opportunity to maximize electroluminescence via activator center excitations, donor-acceptor transitions or band to band transitions per electron as they pass through the thickness of the film. Accordingly, we anticipate that there will be much more gain than that experienced by Cusano. The Cusano amplifier also functions as a light converter, i.e., from uv to light. In our case, the conversion is from a video electronic image to a displayed light image.

Recommended Materials Properties Research:

This study leads to the recommendation that the following research program be pursued. Research should begin with ZnS:Mn since when properly doped, this substance offers all three types of luminescence. Initial doping should be for cathodoluminescence followed by any modification required in doping for electron injected controlled electroluminescence. Research recommended should have the following phases.

1. Deposit ZnS:Mn as a columnar layer using electron beam and resistive evaporation techniques.

2. Deposit ZnS:Mn to cause excellent red-yellow cathodoluminescence.

3. Dope ZnS:Mn as a function of manganese concentration and column length. It will be important to determine if their is an optimum doping density as a function of column length for injection controlled electroluminescence, and to also measure optical attenuation across the visible spectrum.

4. Dope ZnS:Mn for cathodoluminescence to a depth of 1-3 microns depending upon the depth of penetration of the electron beam. Then continue column growth with any change required to optimize manganese concentration for optimum injection controlled electroluminescence along the remaining length of a column.

5. Establish optimum growth conditions for desired columnar structure of different lengths.

6. After completion of studies on ZnS:Mn, continue with new candidate materials. These should include ZnS doped with other chemical activators, ZnSe, CdSe, CDs and ZnCdS. An attractive option is to establish a columnar layer of ZnS and then continue its growth with CDs or ZnCdS. Other combinations also exist. They each offer different luminescent colors and thereby offer in addition to the doping identified above, increased opportunities to develop selected colors including white.

7. There are a host of other dopants that have been used to achieve different colors and brightness levels. For example, in AC thin film electroluminescence phosphors, ZnS:NdF_3 and ZnS:SmF_3 provide red emission with the latter being far brighter; ZnS:Tb/P is a very bright green emitter and ZnS:TmF_3 is a very weak blue emitter. There are many other dopants noted in Tannas

as well as materials suited for electron beam pumped lasers.[17,18]

8. Undertake other materials deposition techniques for improving uniformity of column growth and might prove superior to the Goodwin method.

Columnar layers should be examined for individual column growth characteristics, including 1) uniformity, separateness for column optical isolation, single crystal status versus polycrystallinity, and the manner in which they maintain these characteristics as a function of crystal growth. These examinations should determine their performance for cathodoluminescence, electroluminescence, cathodoluminescence combined with electroluminescence, plus exploring their ability to serve as a traveling wave amplifier as well as to provide laser emission, with and without the application of an electric field.

These tests should be carried out keeping in mind the potential for these materials advancing "the state of the art" in CRT and FED displays, plus front and rear video projectors.

Physical Properties Research:

As each phase of the materials preparation program progresses, there should be continual monitoring of the basic electrical, optical, and luminescent properties of the columnar layers plus their performance when inserted in a display.

Electrical, optical and luminescent measurements of columns should include:

1. Electrical Properties
   Resistivity of columns as a function of length, dopant, and its concentration.
   Ohmic versus junction properties
   Breakdown characteristics
   Aging

2 Luminescent Properties
   Spectral Characteristics as a function of column length- optical absorption..
   Spectral characteristics as a function of dopant material.
   Spectral characteristics as a function of field strength .
   Response Time

3 Optical Properties
   Scatter
   Gain

Display measurements should be made independently for:

1. Cathodoluminescence

2. Electroluminescence

3. Cathodoluminescence plus Electroluminescence

These display measurements should include:

a. Brightness b. Spatial Resolution c. Contrast Resolution
d. Dynamic Range e. Stationary and Dynamic Noise f. Color

In particular, measurements they should stress:

1. **Display light output:**
   a. Cathodoluminescent column light output as a function of beam energy.
   b. Electroluminescent light output as a function of applied voltage across the columnar layer.
   c. Cathodoluminescent plus electroluminescent light output as a function of the beam energy and the applied voltage.

2. **Contrast resolution** as a function of column length.
3. **Spatial resolution** as a function of column length.
4. **Noise.**
5. **Speed of response**.
6. **Dynamic Range**.
7. **Scatter and contrast resolution** as a function of layer thickness (column length). These are to be compared with that from "state of the art" the conventional phosphor powder embedded in a binder.
8. **High resistivities coupled with potential blocking layers** for electrons and holes where possible and appropriate, are attractive features sought to minimize dark current and electroluminescence background. An ability to function at very high field strengths, such as 10^5 to 10^6 Volts/cm without breakdown or charge injection, is most important. These layers should be tested for any electroluminescence associated with dark current followed by the beam turned on for testing video controlled electroluminescence and aging associated with coulombic loading.

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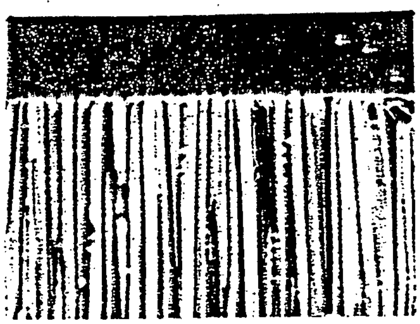
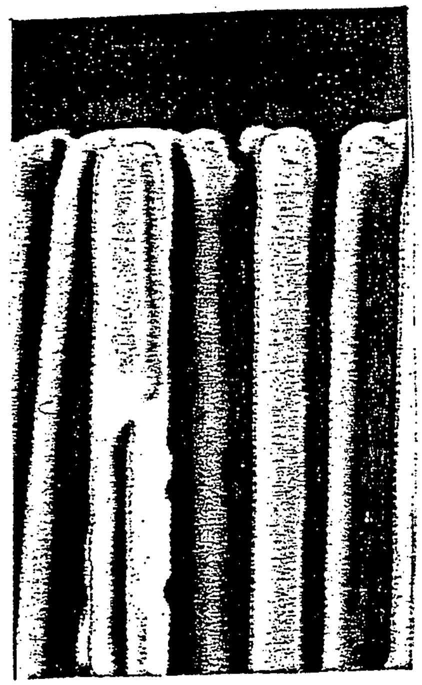


a.



b.

Fig. 1 a. Upper Section of CsI Columnar Growth Scale 1cm = 1 micron

b. Image of a. Magnified x 4

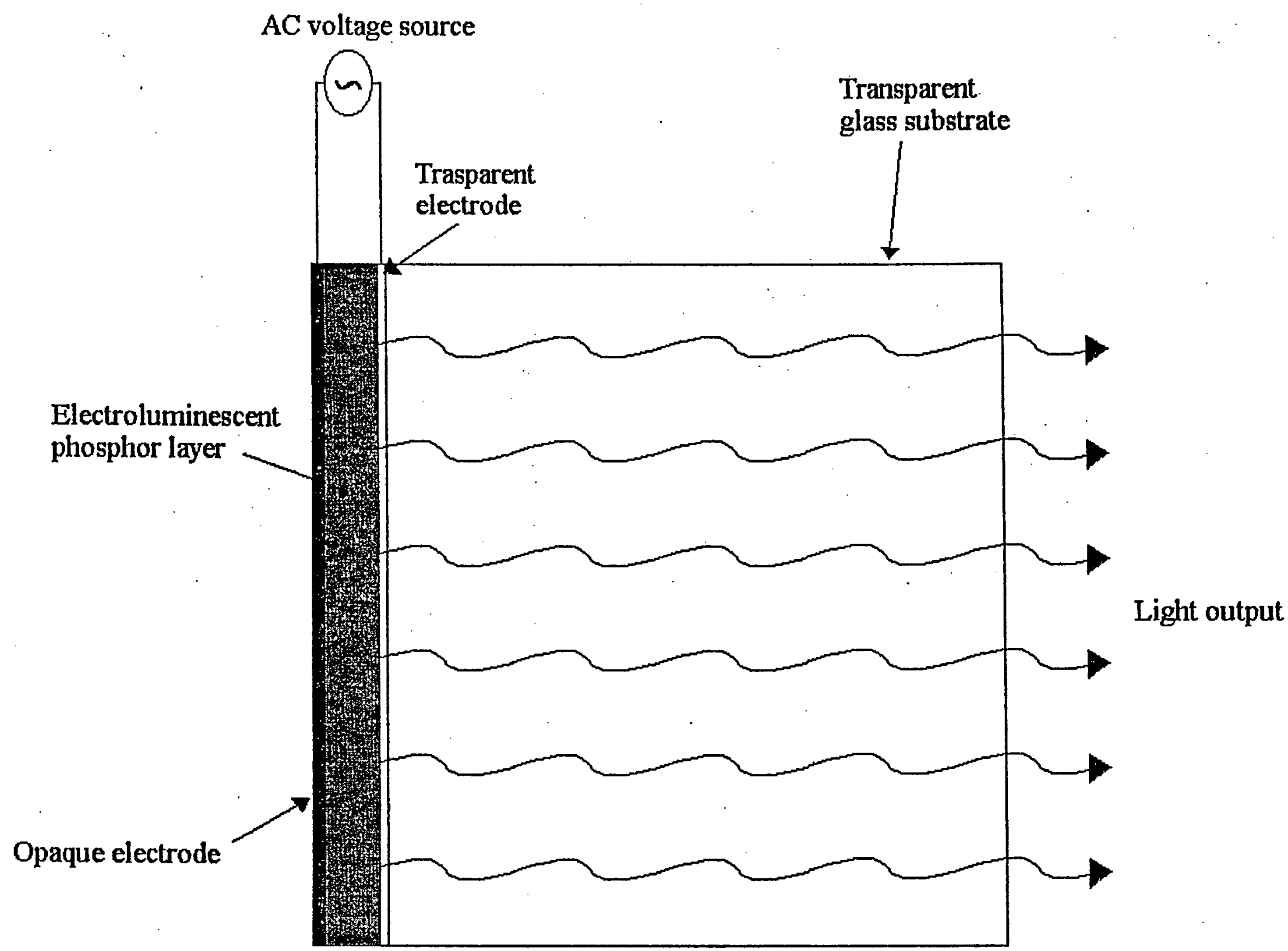


Fig. 2

The AC Electroluminescent Structure

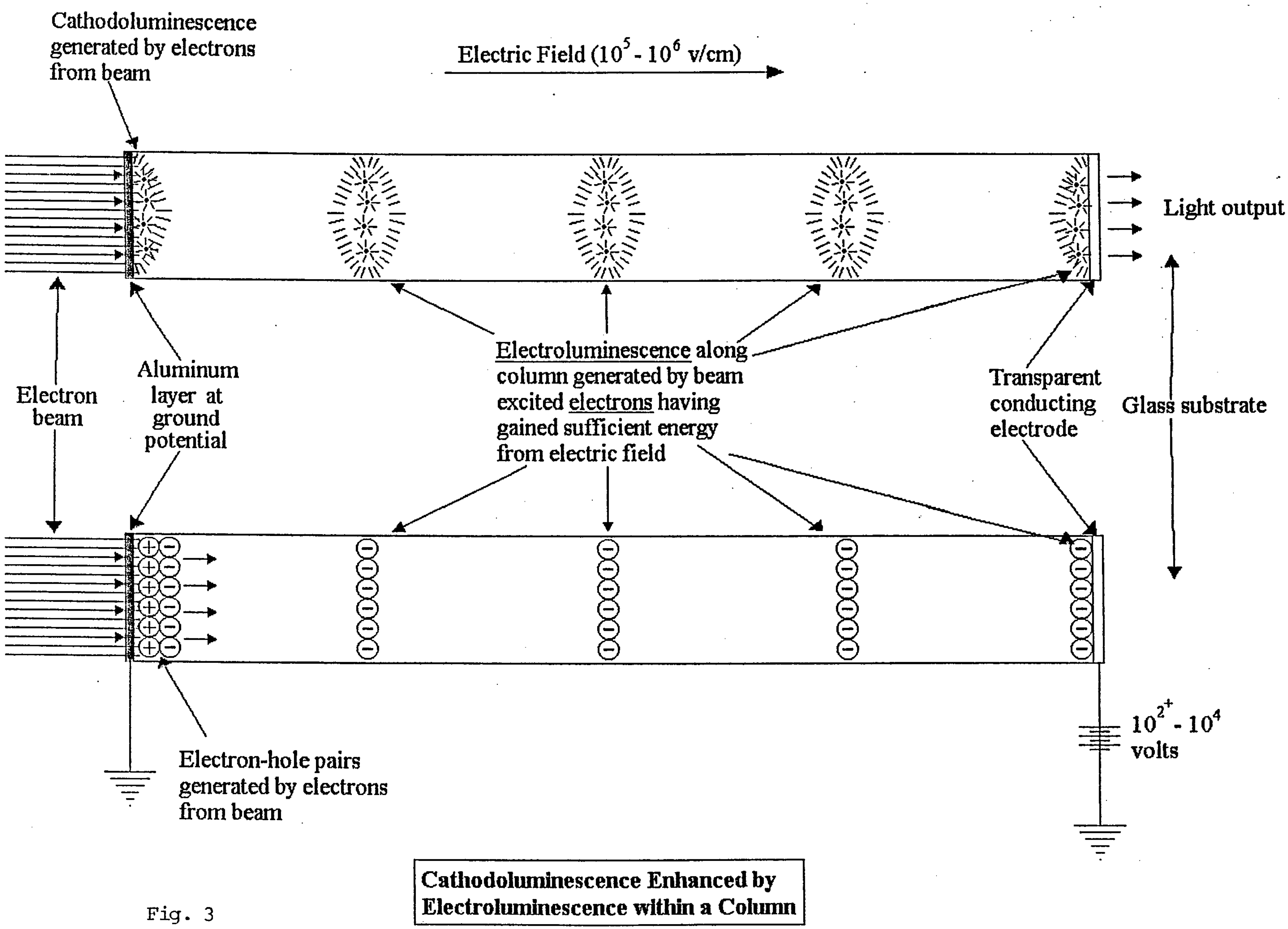
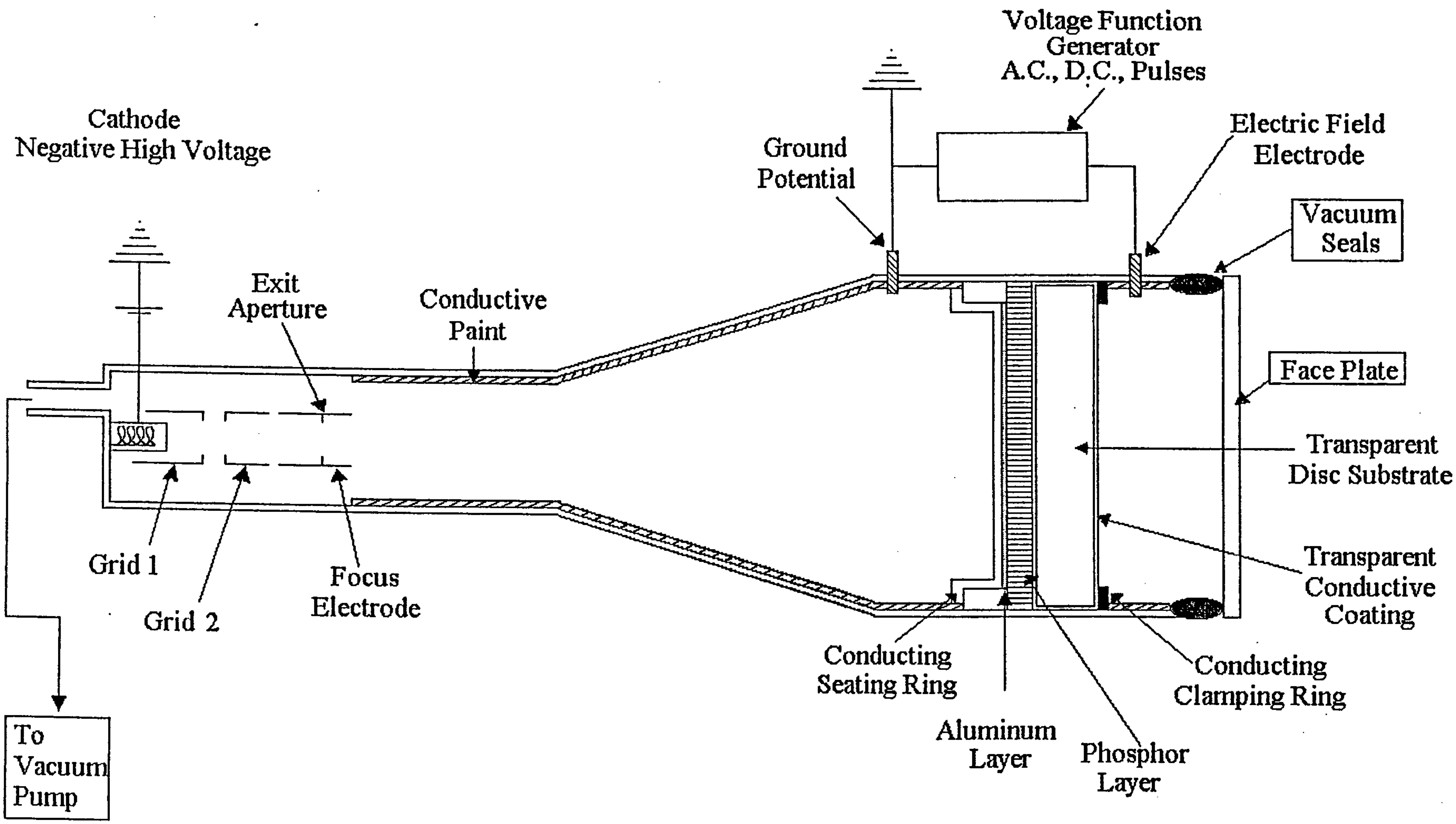

Cathodoluminescence generated by electrons from beam
Electric Field (10^5 - 10^6 v/cm)
Light output
Electron beam
Aluminum layer at ground potential
Electroluminescence along column generated by beam excited electrons having gained sufficient energy from electric field
Transparent conducting electrode
Glass substrate
Electron-hole pairs generated by electrons from beam
10^{2^+} - 10^4 volts
Cathodoluminescence Enhanced by Electroluminescence within a Column

Fig. 3



Schematic of demountable display tube

Fig. 4