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DYNAMIC ASTIGMATISM AND FOCUS CORRECTION OF THE CATHODE RAY TUBE OF ERASME

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Abstract

The principle of programmed astigmatism and focus correction is described. Practical results are given as well as the adjustment procedure. This system has now been used for three years and maintains a spot size of 15 μ over a surface of 120 x 120 mm^2 using a 7" tube with phosphor "A" (Ferranti).

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CONTENTS

1. Introduction

The scanning and measuring system ERASME was specially developed for the analysis of photos from the new generation of bubble chambers, in particular from BEBC (Big European Bubble Chamber), at CERN (reference 1). This system uses for the precision measurement a "flying" spot of light generated on the screen of a cathode ray tube.

In flying spot measuring machines for photos from the medium size bubble chambers such as the CERN 2 m chamber, a spot of up to 30 μm and even more could be tolerated. On these pictures the size of the bubble images is about 25 μm. The contrast is generally good ($K \approx 0.6$) and the film background is uniform.

The photos from BEBC are much more difficult to measure. The contrast of the track images is smaller (sometimes even less than $K = 0.3$). The size of the bubble images varies considerably and can occasionally be as small as 8 μm. Furthermore, as a consequence of the utilisation of brightfield illumination, the film background is non-uniform. The possible presence of other background images, from boiling hydrogen or small solid particles, may further reduce the usable contrast of the tracks.

To determine the position of such tracks all over the picture with an accuracy of two to three micrometres, it is essential that the measuring spot of light remains in the order of the size of the bubble images over the whole area. Thus a spot of more than 20 μm would sensibly degrade the detection sensitivity and the precision on the very faint tracks.

At present, the best 7" cathode ray tubes can produce a spot of 12 μm to 13 μm at the centre of the screen provided that high quality magnetic focusing and a fine grain phosphor are used. If the spot is deflected from the central position it grows considerably unless special precautions are taken.

This paper describes the instrument which keeps the spot shape and size virtually constant over the whole screen. It is called the SSC-unit (Spot Shape Control Unit).

2. Spot Growth Caused by the Deflection Field

Deflecting the electron beam using a high quality coil produces two main aberrations, field curvature and astigmatism.

In Figure 1 the principle of this phenomenon is illustrated. Due to the fact that the different portions of the converging beam are deflected differently, the beam first focuses into a line perpendicular to the direction of deflection. Later it forms a circular section, the circle of least confusion. Further on it focuses to another line parallel to the direction of the deflection and perpendicular to the first line. All other cross sections of the beam are elliptical. The focused lines and the circle of least confusion are located on curved surfaces as indicated in Figure 1.

The other aberrations can normally be neglected on microspot tubes provided that the coils are geometrically well adjusted to the beam, and their field distribution is symmetrical. For further details see, for example, reference 2.

3. Compensation of Field Curvature

The field curvature can be corrected by varying the focal length of the focus coil. This limits the spot growth of a microspot tube to about 30 to 40 μm, depending on the quality of the deflection coil. This method is widely used in CRT systems. Further reduction of the spot growth requires astigmatism correction as a function of the spot position ("dynamic" correction).

4. Compensation of Deflection Astigmatism

If the non-deflected electron beam were free of astigmatism and if the deflection coil produced an ideal field, then the deflection would produce astigmatism which is symmetrical about the centre of the screen. Applying focus correction such that the sagittal surface coincided at any deflection angle with the screen would produce the symmetric pattern shown in Figure 2a. In the case of the tangential surface the distribution of Figure 2b would result.

In most practical cases, however, this symmetry is more or less disturbed due to asymmetries of the beam and of the deflection field. Additional astigmatism is produced and the astigmatic point images (focused lines) are rotated irregularly.

In all cases the astigmatism can be compensated for with two quadrupole coils, with an angle of 45° between their axes of symmetry, aligned coaxially to the electron beam.

4.1 Astigmatism Correction Following Analytically Defined Functions

S.S. Willder (reference 3) has shown that using a very good deflection coil, a satisfactory correction of the deflection astigmatism can be achieved by introducing compensation currents which follow analytically defined functions. In a first approximation the currents must be proportional to the square of the deflection distance from the centre of the screen. If the axes of symmetry of the first coil ("M") are aligned parallel to the X and Y directions and the axes of the second coil ("N") are aligned at 45^{o} to those of "M" the required functions are:

$$I_M = K_M r^2 \sin 2\emptyset = 2 K_M x y$$
$$I_N = K_N r^2 \cos 2\emptyset = K_N (x^2 - y^2)$$

Where K_M and K_N are constants, x and y the deflection distances, in the coordinate system with origin at the centre of the screen, and $\emptyset$ is $\tan^{-1}\left(\frac{y}{x}\right)$.

The second order approximation for the correction currents is given as:

$$I_{M2} = K_M r^2 \sin 2\emptyset - K_{2M} r^2 \cos 2\emptyset = 2K_M xy - K_{2M}(x^2 - y^2)$$
$$I_{N2} = K_N r^2 \cos 2\emptyset + K_{2N}\, 2xy = K_N(x^2 - y^2) + K_{2N}\, 2xy$$

S.S. Willder has also indicated a procedure to take into account a certain asymmetry of the astigmatism distribution by sacrificing the spot size in the centre to minimize the overall spot growth.

4.2 Comparison Between Correction Following Analytically Defined Functions and Values of Correction as Determined Experimentally

S.S. Willder succeeded in one case in keeping the size of the spot between 14 μm and 19 μm on a 188 mm (9-inch) Q4 screen using the second order correction. This means the spot growth could be limited to 35%.

In ERASME a 7" tube is used (Ferranti type 18/75 AFJ) because it was found that the "A" phosphor permits a spot size which is smaller by $\frac{7}{9}$ compared with the minimum spot size on a 9" - Q4 tube. This means that both tubes have the same relative resolution (reference 4). One would therefore expect spot sizes between $14 . \frac{7''}{9''} = 11$ μm and $19 . \frac{7''}{9''} = 15$ μm on the 7" tube using the analytically defined second order corrections. In practice the spot growth was found to be considerably larger.

It was, however, possible to keep the spot size as small as 10 μm all over the screen, by optimizing the correction currents for focus and astigmatism at the individual positions.

Up to now the spot is defined as the diameter at 60% intensity. We normally measure at 50% intensity which results in 18% bigger spot sizes if a Gaussian distribution of the intensity is assumed. In the following all spot diameters are indicated at 50% intensity.

To give an impression of the difference between the correction currents as calculated from the analytical formulae and the optimum values found experimentally, the results have been plotted in a 3-dimensional representation (Figure 3). The 81 coordinates of the measuring points on the screen are situated in the X/Y plane. The correction currents are represented by amplitudes in Z. The analytically defined values are shown on Figure 3a. The plots on Figures 3b and 3c show the optimum correction currents found experimentally on two different tube-coil combinations. The comparison of Figure 3a with Figures 3b and 3c shows that the values for the correction "M" are fairly close to the theoretical function. However, the values for "N" are rather different from it and also differ from each other.

A possible explanation for the irregular astigmatism which we find experimentally may be that in ERASME 60 μH deflection coils are used whereas S.S. Willder used a 250 μH coil. The lower inductance coil has fewer windings and it is therefore more difficult to produce a perfect deflection field.

4.3 Tolerances of the Correction Currents

Measurements have shown that varying the correction currents for astigmatism correction by ± 5% of the total required variation has practically no effect on the form of the spot.

The permissable tolerance of the dynamic focus is only ± 2% for 10% spot growth at 15 μm spot size (at 50% intensity).

5. Control of the Compensation Currents to Follow the Experimentally Determined Values

In view of the big differences between the corrections following the analytically defined functions and the optimum corrections as determined experimentally it was considered preferable to employ a method which approximates the optimum values within the tolerances indicated under 4.3. This procedure permits limitation of the spot growth to about 10% over the entire screen.

5.1 Sets of Discrete Values (Stepwise Approximation)

In this mode discrete values are stored in a memory from which the values are read according to the spot position in X and Y. To maintain the current values within the tolerances mentioned under 4.3 a total of 10.000 reference points would be needed for the focus and 2 x 1.600 points for astigmatism correction. This estimate is based on the theoretical formulae derived by S.S. Willder (3) and assumes equidistant points. It is obvious that it is unrealistic to use such a big number of reference points whatever the implementation of this method might be.

5.2 Two-dimensional Function Generator

The required correction currents are derived from a generator of a polynomial in X and Y of which the coefficients are stored. This generator can be analogue or digital. For a close approximation, a complex network would have to be used with the resulting difficulties of long term stability if it were analogue, or the speed if it were digital.

5.3 Linear Interpolation between a Number of Discrete Values

It was found that the most flexible method of achieving a good approximation to an arbitrary smooth function in X and Y was the use of a combination of both methods. This approach uses a grid of equidistant points over the screen for which the values of compensation are stored. For positions between these points the required currents are calculated by linear two dimensional interpolation in a simple analogue computing network.

6. Description of the Unit for Dynamic Focus and Astigmatism Correction (The SSC-Unit)

6.1 Principle of Operation of the SSC-Unit

In our device the spot position is controlled at any moment by digital values for the X and Y directions (16 bits per coordinate). The three most significant bits define 9 x 9 = 81 locations on the screen. At these points the correction currents which are required in the dynamic focus coil ("F") and the two dynamic astigmatism coils ("M" and "N") are measured experimentally. The results are stored in a hardware memory.

During normal operation when the spot is moving on the screen, the digital deflection values are used to read out the required correction currents. The first three bits of each word define the four measured values between which the spot is situated. The rest of the word is then used to calculate the linear interpolation between these four values.

This procedure permits the approximation of any required function of the variables X and Y.

In Figure 4 the block diagram of the SSC-unit is shown. On the right of the picture there are three identical channels, "F" for dynamic focus and "M" and "N" for dynamic astigmatism corrections. Each of them has its own memory for the 81 measured values. As the values have only to be changed rarely, potentiometers are used as analogue memories. On the left side there are the two digital inputs for the X and Y coordinates. Bits 13 to 15 are used in the grid decoder and bits 4 to 12 in the D/A converter for the generation of the interpolation values ΔX and ΔY.

The third input on the left side is only used in the mode of "computer aided adjustment" as described under 9.2. In this mode the correction currents are under direct computer control arranged so that the X-channel controls the current "F", the Y channel the current "M" and the third channel the current "N" directly. For manual adjustment each channel can be switched to manual control.

At the bottom of figure 4 a display unit is indicated. This consists of an array of 9 x 9 = 81 lamps mounted into the frontplate of the SSC-unit. The grid decoder illuminates the four lamps corresponding to the four selected corner points.

This facility was originally intended to be used only during the adjustment procedure. Eventually it was found to be very useful for software development and hardware testing indicating the approximate position of the spot and hence, very roughly, the activity of the CRT under program control.

6.2 Principle of the Linear Interpolation Within One Grid Square

The principle of the interpolation is explained with reference to Figure 5.

The value of the current at any point between the two corner points I_1 and I_2 is

$$I_{12} = I_1 + \frac{\Delta x}{\Delta x_{max}} (I_2 - I_1) \qquad (1)$$

Similarly at the same X coordinate between the two corner points I_3 and I_4 the current is

$$I_{34} = I_3 + \frac{\Delta x}{\Delta x_{max}} (I_4 - I_3) \qquad (2)$$

Interpolation is then made in Δy direction between I_{12} and I_{34} to find the the current I_p.

$$I = I_{12} + \frac{\Delta y}{\Delta y_{max}} (I_{34} - I_{12}) \qquad (3)$$

combining equations (1), (2) and (3) yields:

$$I = I_1 + \frac{\Delta x}{\Delta x_{max}} \left[(-I_1 + I_2) + \frac{\Delta y}{\Delta y_{max}} (I_1 - I_2 - I_3 + I_4) \right] + \frac{\Delta y}{\Delta y_{max}} (I_1 + I_3) \quad (4)$$

6.3 Transition From One Grid Square to Another

The most critical situation for the analogue interpolation circuit arises when the spot is moving across the border between two neighbouring grid squares. At this moment a new set of corner values has to be read in and there is a danger of "glitches" and discontinuities. If the same procedure as described in 6.2 (Figure 5) were used, all corner values would change and the interpolation factors Δx resp. Δy would jump from Δ_{max} to zero.

With the arrangement shown in Figure 6, a smooth transition between neighbouring grid squares is assured. It takes advantage of the fact that at the border between two grid squares only two corner values contribute to the calculation. Therefore the two other ones can be switched to new values without causing any perturbation for the output signal. If the spot moves for example from square I to II crossing the line 2 - 4, only the values 1 and 3 are switched. The interpolation value Δx had just reached Δx_{max}. It now switches to $(\Delta x_{max} - \Delta x)$. Since at this moment Δx is zero the interpolation voltage remains unchanged. Thus neither the switching of the corners nor the transition to the new interpolation value causes any transient.

This is demonstrated in Figure 7 showing the oscillogram of the correction current for dynamic focus during the movement of the spot at a speed of 10 $\mu m/\mu s$.

In Figure 6 the numbers in the corners of the squares represent the numbers of the inputs to the interpolation circuit (Figure 9). It can be seen that the lines 2 - 4 - 3 and 3 - 4 - 3 are axes of symmetry. In the left two squares Δx is used for the interpolation in the x direction, whereas in the right two squares $(\Delta x_{max} - \Delta x)$ is utilized for this purpose. In the lower two squares ΔY controls the interpolation in Y direction whereas $(\Delta Y_{max} - \Delta Y)$ performs this task in the upper two squares.

Figure 8 shows the selection sequence of the corner points and the interpolation voltages over the whole measuring area.

6.4 The Electrical Interpolation Circuit

Figure 9 shows the block diagram of the electrical circuit which is used for the linear interpolation between four grid points. On this picture the equation for the interpolation is indicated. It is identical with eq. 4 of paragraph 6.2 with the exception that the general interpolation values

X' and Y' are used instead of $\frac{\Delta x}{\Delta x_{max}}$ and $\frac{\Delta y}{\Delta y_{max}}$. The reason is that according to the grid square selected, X' and Y' are defined differently (see 6.3)

$$X' = \frac{\Delta x}{\Delta x_{max}} \quad \text{or} \quad \frac{\Delta x_{max} - \Delta x}{\Delta x_{max}}$$

$$Y' = \frac{\Delta y}{\Delta y_{max}} \quad \text{or} \quad \frac{\Delta y_{max} - \Delta y}{\Delta y_{max}}$$

Obviously one is the complement of the other. How these values change according to the position on the screen can also be seen on Figure 8 left and bottom.

Since multipliers are critical elements and more expensive than operational amplifiers, the equation was arranged to require a minimum of multipliers.

7. Method of finding Experimentally the Required Correction Currents

To find experimentally the optimum combination of the three compensation currents F, M, N, for each of the 81 points to be stored in the memory, several methods can be used. The most practical one replies on the saturation of the phosphor.

For all methods it has to be assured that the correction currents are measured at the normal beam current. This is important as the aberrations of the spot are somewhat dependant of the beam current (at least in the case of Ferranti tubes).

The smaller the area on the screen to which the electron beam is concentrated the larger is the power per unit area of the phosphor. Near the minimum spot size the light output saturates. That is to say the light output will be a minimum at optimum spot correction. Tests have shown that it is quite easy to find the smallest possible round spot by searching for the minimum photomultiplier current. For this purpose the compensation currents are changed one at a time to find the relative minimum of the photomultiplier current. This procedure converges very quickly to the optimum. Fortunately there exists only one minimum of light output of the spot. In our case we place a repetitive raster of about 200 x 200 μm^2 at the location of the point to be measured using normal scanning speed at normal beam current.

This method does not require any additional hardware as the output of the four reference photomultipliers arranged around the CRT screen is available at the frontplate of the video processor. Furthermore this method is very well suited for computer aided adjustment as to be described under 9.2.

The criterion of the phosphor saturation is also used to quickly check the correction of the spot over the measuring field by running a TV-like scan across the whole area and looking at the photomultiplier output with an oscilloscope.

8. Results

All tests have been performed on a Ferranti tube type 7/75 AFJ.

8.1 Spot Size

On a tube which had a spot size of 12 to 13 μm (diameter at 50% intensity) in the centre, the spot could be maintained within 15 μm within a square of 124 x 124 μm^2. We are confident that the same result can be achieved over the whole 160 mm Ø screen.

8.2 Uniformity of the Spot Size

Figure 10 gives an idea of the uniformity of the spot size over the whole of the measuring area. Three scan lines have been selected, one at the top edge, one across the center and one at the bottom edge of the measuring area. The test picture consists of transparent lines of 10 μm and 25 μm alternately at a spacing of 200 μm on black background. On the picture the envelope of the pulses from both the 25 μm and the 10 μm lines can be seen to be virtually the same on the three scans. The amplitude of the pulses is a real measure of the relative modulation as the video signal has been divided by the output of the light monitoring photomultipliers. This good result demonstrates at the same time the excellent quality of the projection lens. Small local variations are caused by imperfections of the test grid.

To demonstrate the improvement due to dynamic astigmatism correction the same test has been made employing dynamic focus correction only and static instead of dynamic astigmatism correction (Figure 11b). On Figure 11a the same line is scanned using normal corrections. On Figure 11c the output of the monitoring photomultipliers is displayed (in opposite polarity). The relation between light intensity and modulation is clearly visible which permits the use of this criterion as a measure of spot quality as described under 7.

8.3 Maximum Usable Spot Velocity

No degradation of the spot was observed up to a scanning speed of 40 μm/μs. The settline time to the new correction currents after a large jump is 40 μs in the worst case. This means maximum variation of the corner values and the interpolation voltages. This time is much shorter than the settling time to one least count (1 : 64000) of the magnetic material of the deflection coil.

8.4 Variations of the Adjustments as a Function of Time

One tube has been running for 16.000 hours during $2\frac{1}{2}$ years without mechanical readjustment. The adjustment of the SSC-unit was checked at intervals of more than 6 months. Only very small changes were necessary. In Figure 12 the required correction currents measured at the beginning of the lifetime and after 16.000 hours of operation are plotted. It can be seen that the distribution is very near to the one found at the beginning of the lifetime.

9. Future Plans

9.1 Automatic Checks of Spot Quality

ERASME is now in a phase where much effort is being put into computer controlled tests of the various parameters of the machines which contribute to the measuring quality. In this context regular tests are foreseen to check automatically the distribution of the light output of the CRT over the screen. As explained before this is a means to check the quality of the spot. There is a D/A converter in the video signal processor sending the information about the light intensity of the spot to the computer. This information is available from the four photomultipliers arranged around the surface of the CRT.

9.2 Computer Aided Adjustment and Supervision of the Spot

This is the final step of automation. In a special mode as marked on the block diagram, Figure 4, the correction currents "F", "M" and "N" can be controlled directly by the computer. This facility will be used to automatically search for that combination of the three currents which results in the minimum light output of the photomultipliers and therefore for the optimum spot size and shape. It will thus be possible to print automatically a list indicating the values to which the memory has to be set. During normal operation the program will compare the values found during the optimisation procedure with those produced by the SSC-unit under normal operation. It will inform the operator as soon as the difference between these two values exceeds a certain tolerance. It would be a logical consequence to ask the computer to load the memory directly. This is not foreseen in the near future as it would require too many hardware changes and corresponding expenditures.

10. The SSC Hardware

Figures 13 and 14 illustrate the layout of the SSC-unit.

11. Acknowledgements

We would like to thank Drs. E. Quercigh and D. Lord for their encouragement and support.

Mr. J. Oropesa contributed to the development of the SSC-unit by performing the measurements on the CRT's and discussing the results.

Dr. Hans Drevermann programmed the computer controlled tests.

Mrs. B. Jeremiah prepared the 3-dimensional plots reproduced on Figures 3 and 12.

12. References

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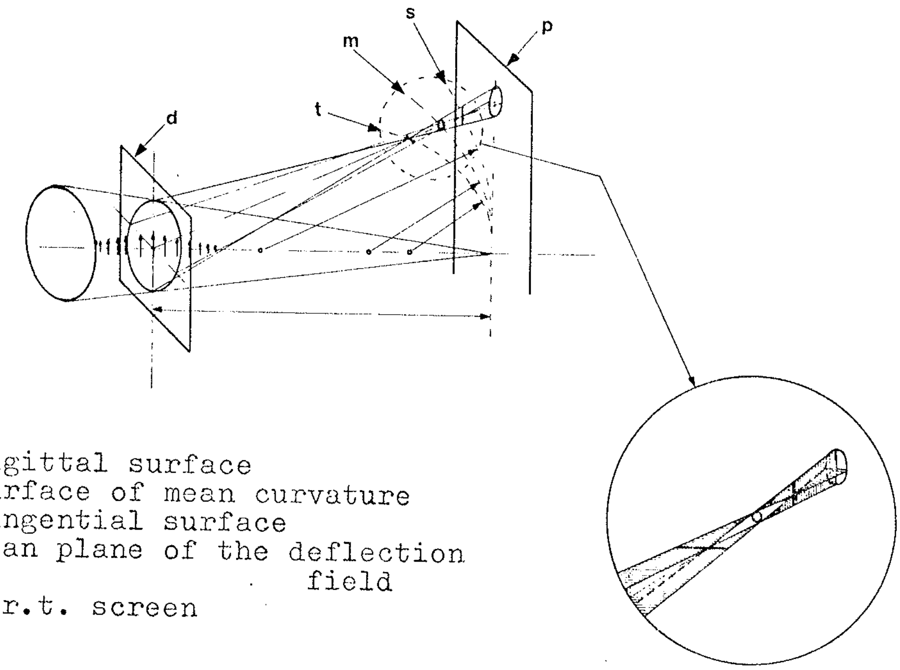
3. S.S. Willder: "The Correction of Deflection Astigmatism in Microspot Cathode Ray Tubes". J. Phys. D: Appl. Physics, 1971, Vol. 4, p. 27-38.
4. H. Anders et al: "LUCY, a CRT film measuring device - a brief description of the prototype and results of detailed hardware performance measurements". CERN - DD/DH/70/9.



s. sagittal surface
m. surface of mean curvature
t. tangential surface
d. mean plane of the deflection field
p. c.r.t. screen

FIG. 1 Principle of field curvature and astigmatism introduced by magnetic deflection

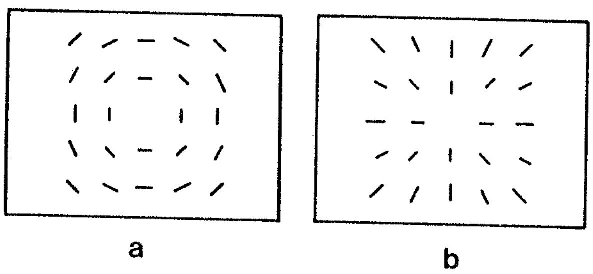


FIG. 2 Stigmatic images on the screen surface

a. Sagittal foci

b. Tangential foci

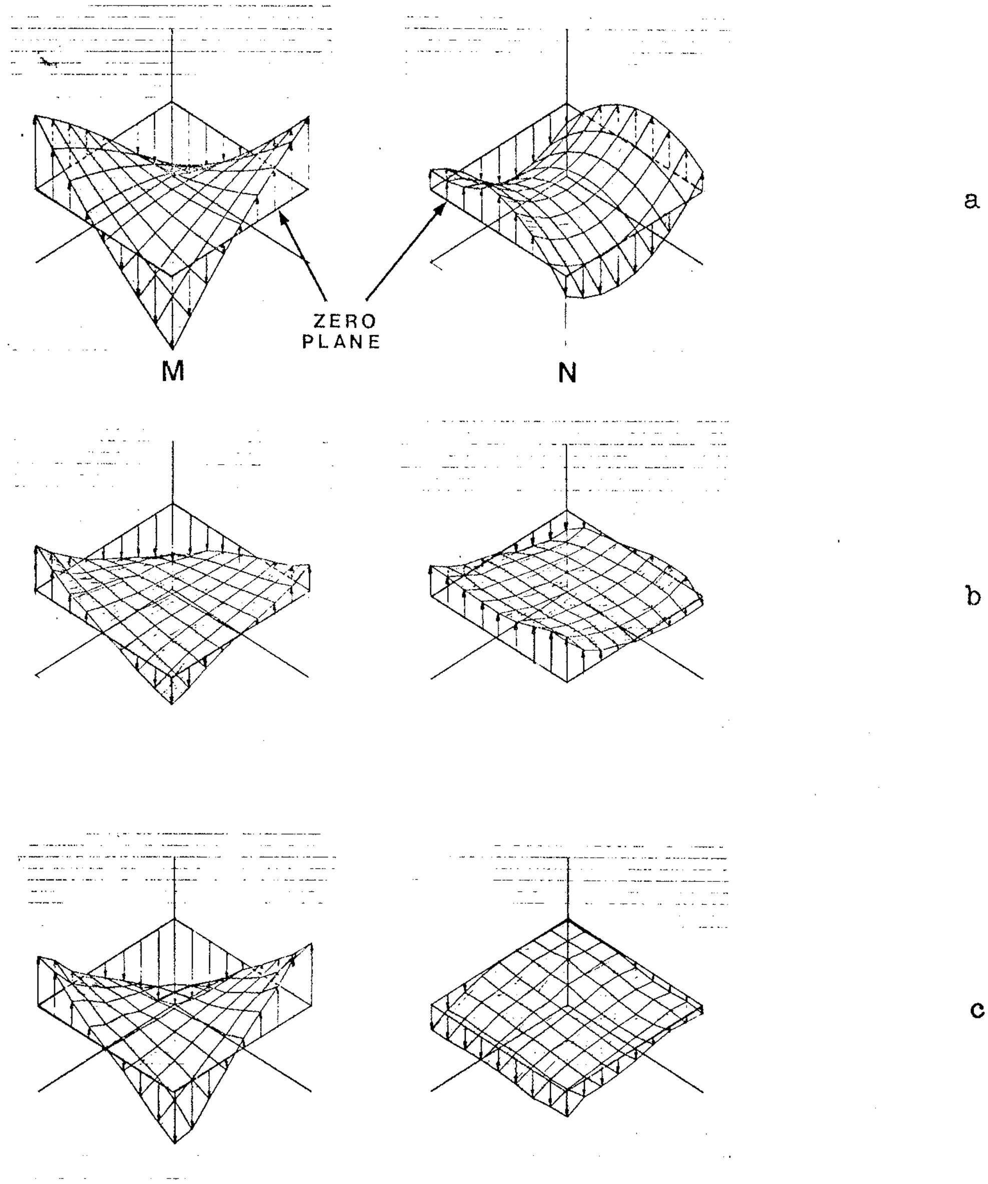


FIG. 3 Plot of the magnitude of the currents in the quadrupoles for astigmatic correction M and N

a. As defined by analytical functions

b. and c. Optimum currents as measured experimentally

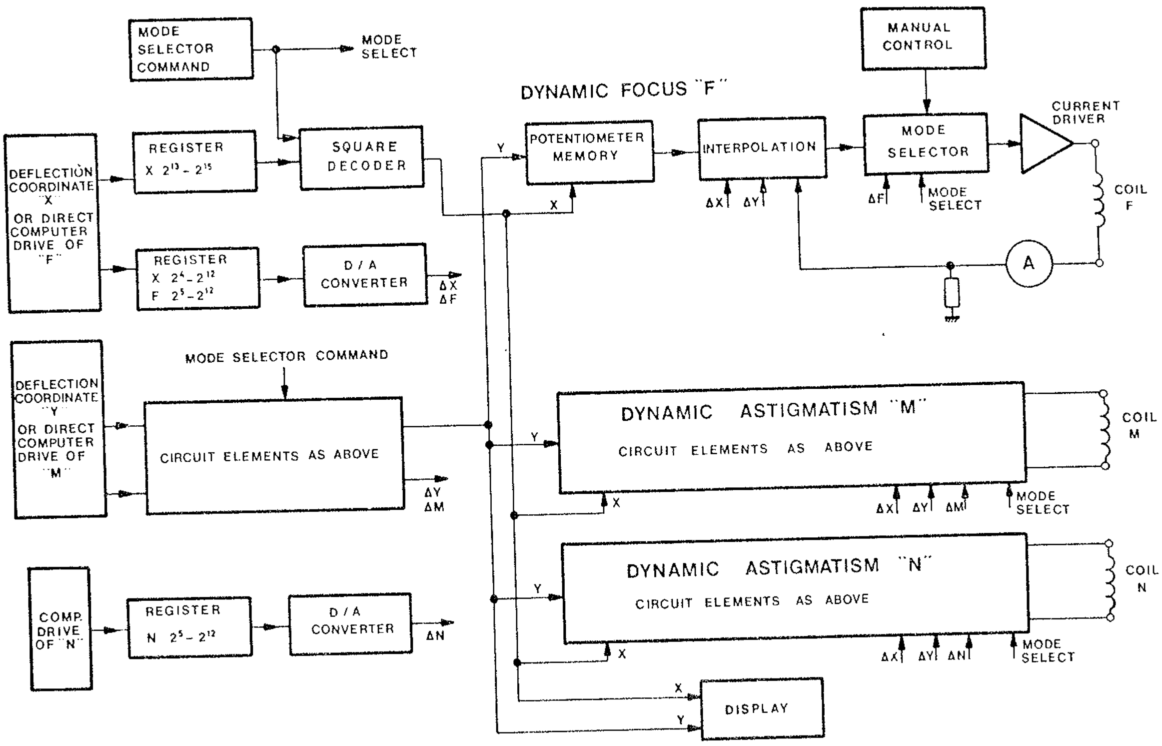


FIG .4 Block diagram of the SSC unit

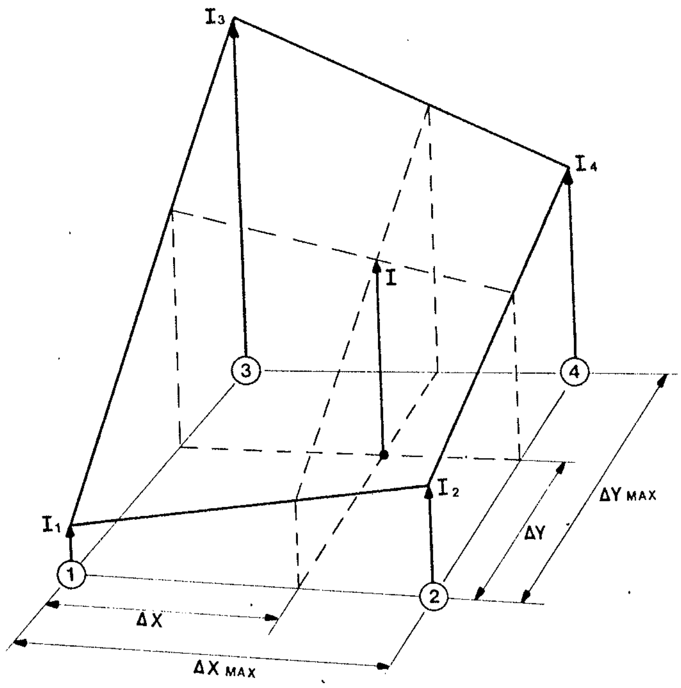


FIG. 5 Principle of interpolation between four grid points

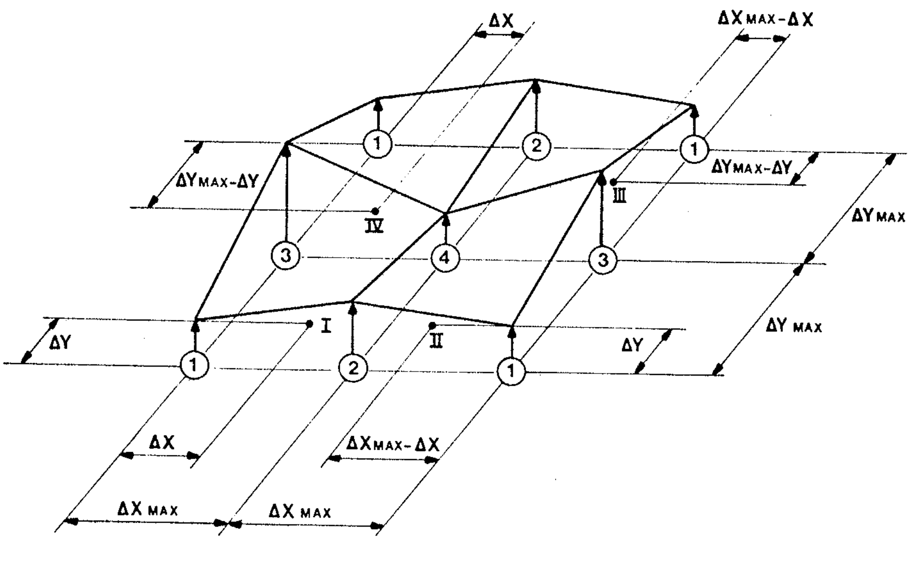


FIG. 6 Interpolation in neighbouring grid squares

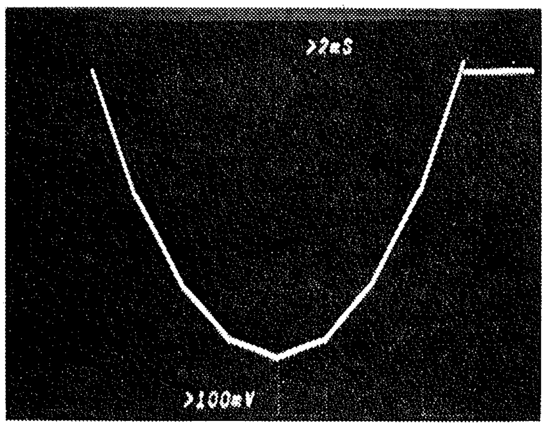


FIG. 7 Oscillogram of the dynamic focus current during one scan line across the measuring area

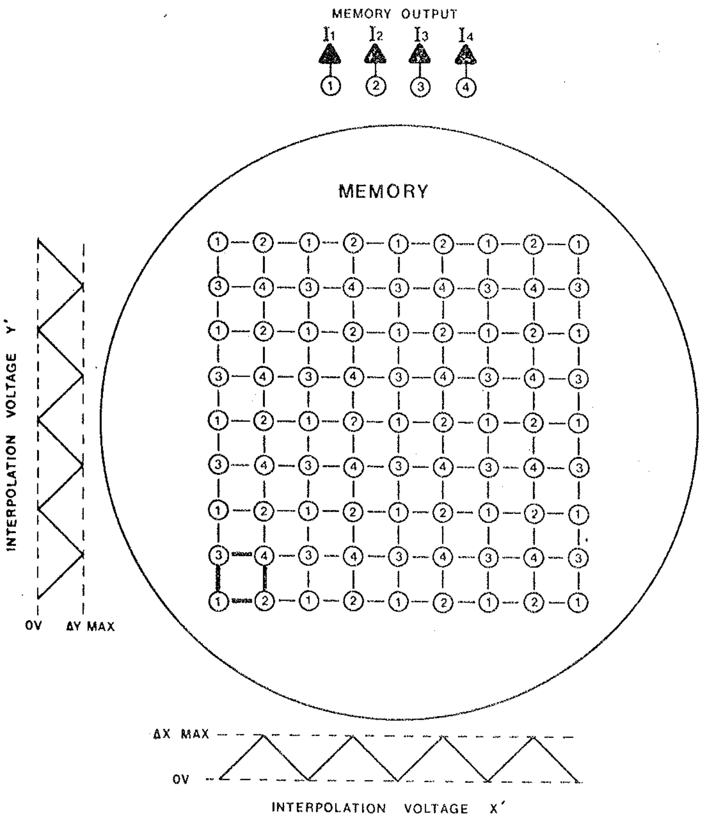
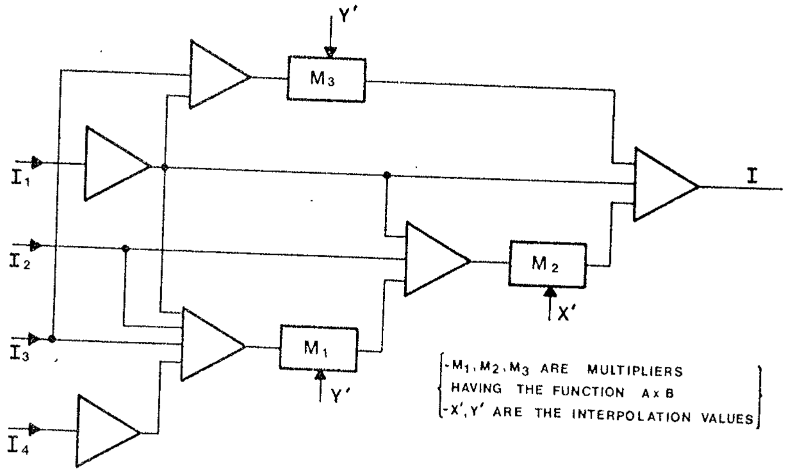


FIG. 8 Arrangement of the 81 memory values and the interpolation values X' and Y' as a function of the position on the screen.

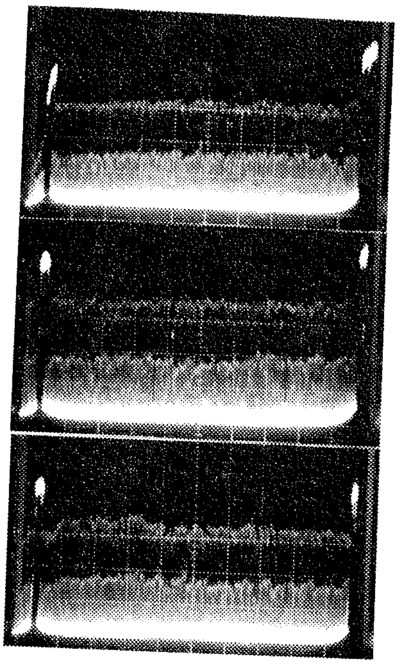


OUTPUT $I = I_1 + X' \left[-I_1 + I_2 + Y'(I_1 - I_2 - I_3 + I_4) \right] + Y'(-I_1 + I_3)$

$$X' = \frac{\Delta x}{\Delta x_{max}} \quad \text{or} \quad \frac{\Delta x_{max} - \Delta x}{\Delta x_{max}}$$

$$Y' = \frac{\Delta y}{\Delta y_{max}} \quad \text{or} \quad \frac{\Delta x_{max} - \Delta y}{\Delta y_{max}}$$

FIG. 9 Block diagram of the circuit for linear interpolation between four grid points. The interpolation values X' and Y' are defined differently according to the different grid squares.



a

b

c

FIG.10 Uniformity of the spot size over the whole of the measuring field.
Modulation generated by a scan:

a. At the top
b. In the centre
c. At the bottom of the measuring area

Test pattern 10µm and 25µm transparent lines at 200µm spacing on a black background.

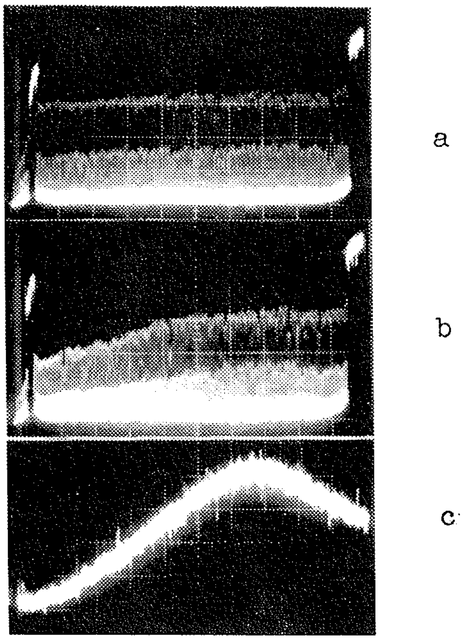


FIG.11 Improvement of the resolution by dynamic astigmatism correction.

a. SSC unit running normally
b. Only dynamic focus, no dynamic astigmatism correction applied.
c. Light output of the spot during scan b.
Note: Inverted polarity, minimum light output at maximum signal amplitude.

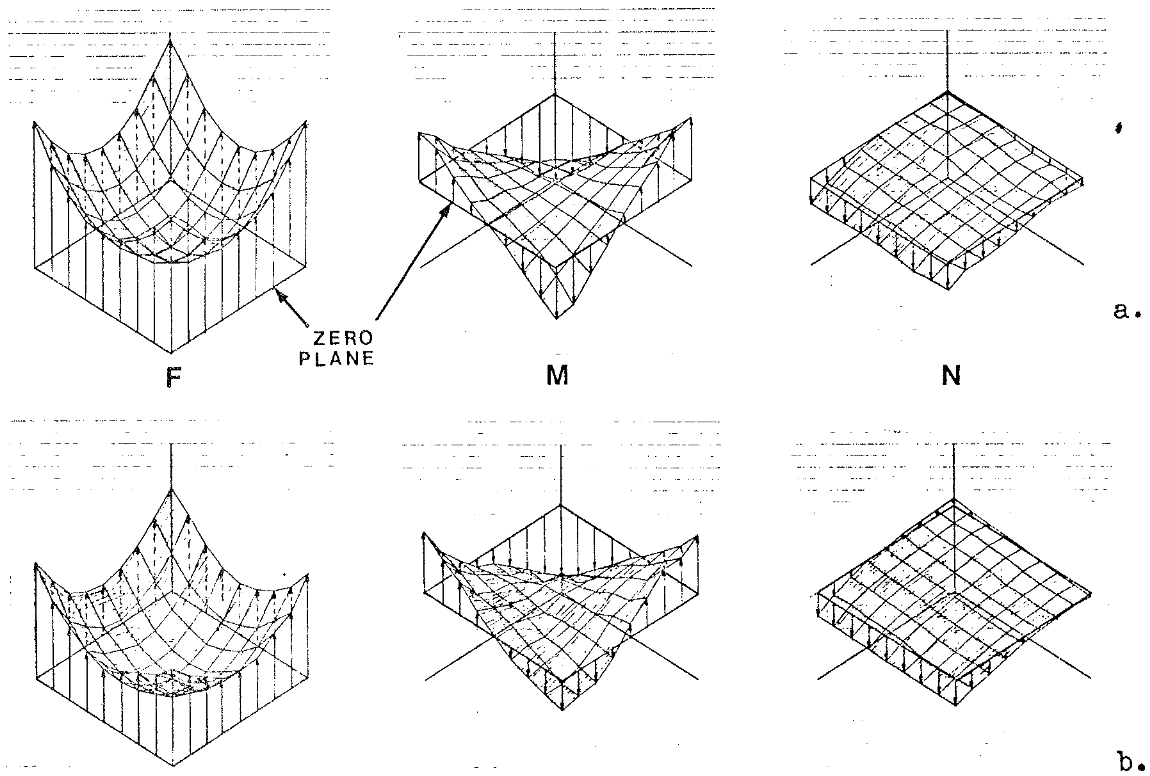


FIG.12 Required correction currents F,M and N
a. At the beginning of the lifetime of a CRT
b. After 16.000 hours running, no mechanical realignment had been made.

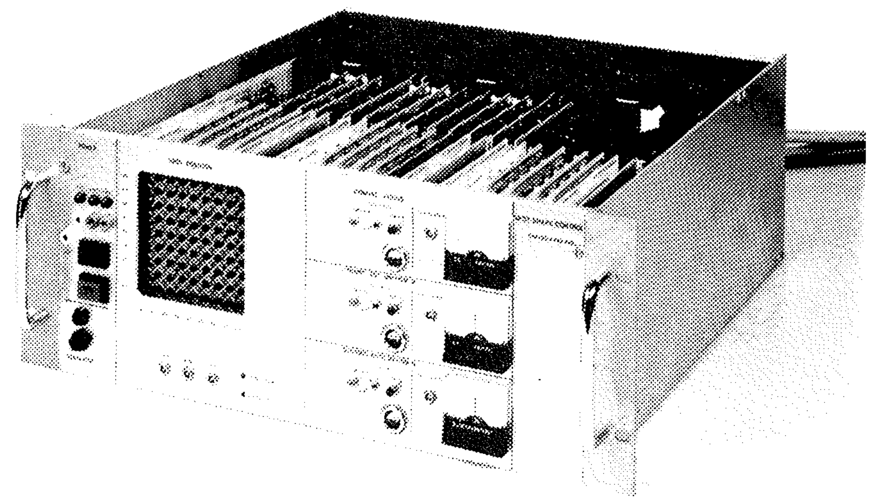


Figure 13 - The SSC Chassis

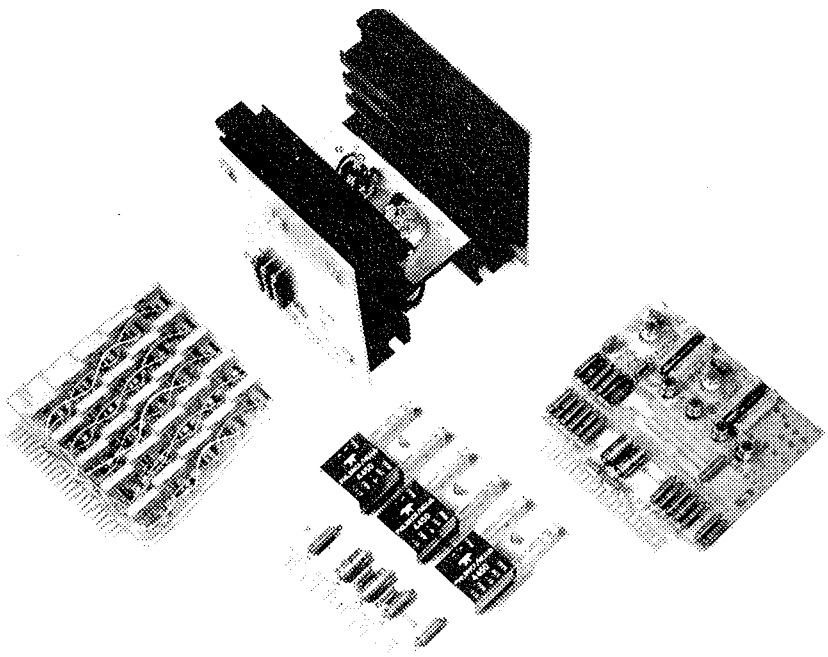


Figure 14 - Typical Components of the SSC Unit