CHAPTER V

ELECTROLUMINESCENCE

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5.1 INTRODUCTION

Electroluminescence (EL) is the phenomenon of light emission by luminors due to the sole action of electrifield (a.c. or d.c.)

During this process, electrical energy is converted into light energy. In the process, radiative system is excited and mechanism of light generation is evolved.

In the mechanism of light generation, radiative and non-radiative transitions are to be considered. These transitions are discussed in chapter I. The different exciting mechanisms are also considered in chapter I.

Study of voltage and frequency dependence upon brightness, are the important features of electroluminescence.

In the prsent investigation, studies on voltage and frequency of time averaged electroluminescent brightness are studied, to obtain the following information —

1] Voltage dependence of EL brightness.
2] Frequency dependence of EL brightness.
3] Effect of activators on EL brightness.
4] Mechanism of EL.
5] Kinetics involved in the process.

5.2 THEORETICAL BACKGROUND

5.2.1 RELATION BETWEEN BRIGHTNESS AND APPLIED VOLTAGE

The electroluminescence brightness depends on exciting voltage. A number of mathemtical relations between the quantities are proposed by various workers. There appears to be considerable disagreement as regards the exact quantitative relationship. The differnt mathematical forms are given here.

Destraiu(1) observed that, the time average of the emission intensity of electroluminescent zinc sulphate phospher increases, exponentially with increasing amplitude of exciting alternating filed. The first relation proposed by him is

$$B = a.e^{(-b/v)} \quad .. \quad (5.1)$$

where 'B' and 'V' are brightness and voltage respectively and 'a' and 'b' are constants independent of 'v' but, dependent on temperature, type of phosphor and frequency of applied voltage. The relation is amenable to simple theoretical interpretation(2) . Later, Destriau(3) changed this to,

$$B = av^n . e^{(-b/v)} \quad .. \quad (5.2)$$

with 'n' being a constant.

For single crystals of ZnS, a relation

$$B = av^n \left[\exp \ (-b/\sqrt{v}\ ) \right] \quad (5.3)$$

is given by Alfrey and Taylor.(4) This equation with n = 1 is found to hold good for ZnS:Mn films(5) . The equation (5.3) with n = 0 reduces to

$$B = ae^{-b/\sqrt{v}} \quad .. \quad (5.4)$$

This equation was first employed by Alfrey and Taylor (4) and Zalm et.al.(6, 7). Zalm and his co-workers(6, 7) have reported that, this equation is valid over seven decades of brightness for microcrystalline ZnS phosphors.

Lateron Thronton and others(8, 9, 10) have shown that, the equation (5.4) holds only at low voltage but, at highvoltage the equation

$$B = a.e^{(-b/v)} \quad .. \quad (5.5)$$

works more satisfactorily.

Lehmann (11) found the emission of individual particles to obey equation (5.5) and showed that summation of the output of large number of particles leads to the normal equation (5.5) viz.

$$B = ae^{-(b/v + vo)} \qquad .. \qquad (.5.6)$$

was first proposed by Destriau and Ivey (12) and subsequently used by Morehead(13) with some success in ZnS and ZnS:Cu,Cl.

For microcrystalline ZnS activated with Cu. Howord et al.(14) and Lehmann proposed.

$$B = aV e^{(-b/v + v_o)} \qquad .. \qquad (5.7)$$

where b and Vo increase slowly with frequency.

On the basis of exhaustion barrier theory Taylor (15) deduced the following relation,

$$B = B_o e^{-(Vo/V)^{\frac{1}{2}}} \qquad .. \qquad (5.8)$$

where as on the basis of impact ionisation mechanism Nagy(16) derived the following relation -

$$B = a.e.^{[-b/(1+cv)^2]} \qquad .. \qquad (5.9)$$

Lu y ckz and Stokkink(17) reported a relation,

$$B = ae^{(bv)} \qquad .. \qquad (5.10)$$

for microcrystalline ZnS:Mn

Harman and Raybold (18) have suggested the Power law relation,

$$B = a\ (V - V_o)^n \qquad .. \qquad (5.11)$$

For ZnS phosphors with $n = 3$, a similar expression with $Vo = 0$ and $n = 2.5$ was given by Dimmer (19) for single crystal of ZnS and was found to be valid at high voltages over five decades of brightness. Halsted and Kollar (20) used equation (5.11) with $Vo = 0$ and $n = 7$. Zalm et al.(21) used it with $n = 3.5$ Gaur and Ranade (22) used this equation with v=o and n = 6.5 for CaS:Ag phosphors. Lawangar and Pawar(23) used equation (5.11) with Vo = 0 for CaS:Bi:Pd phosphors.

On the basis of Pipr and Williams theory Howard et al.(14) obtained another relation as,

$$B = av^{3/2} \left(1 - \frac{3v^{\frac{1}{2}}}{c}\right) e^{(-c/v^{\frac{1}{2}})} \quad .. \qquad (5.12)$$

with 'a' and 'c' are constants. Vlase nka and Popkov(24) have found another empirical formula for film panels, viz

$$B = g.e^{(-\sqrt{v}/h)} \quad .. \qquad (5.13)$$

where 'g' and 'h'are constants.

Chan and Yu(25) have shown that, EL emittance of film panels depends on various parameters, such as composition and aging of panel and applied voltage. They have studied evaporated film panels of ZnS:Mn Cu,Cl and have given an empirical formula

$$B = A.e^{(-G/F + \sqrt{v})} \quad .. \qquad (5.14)$$

where 'A', 'G' and 'F' are functions of operating time and can be regarded as constants during any measurement of EL emittance.

Z Porada(26) applied the EL model suggested by Alfrey and Taylor(27), to explain the observed EL emission, excited by high energy electrons in the strong electric field of the metal semiconductor junction and arrived at the equation,

$$B = B_o.e^{(-A/f)}.e^{(-\alpha / \sqrt{v})} \quad .. \qquad (5.15)$$

where 'B_o' is a constant independent of units in which 'B' is expressed, 'A' is a parameter dependent on the technological conditions under which samples are prepared and temperature, 'f' is a frequency and α is a parameter dependent on the value of the critical intensity of the electric field causing ionisation of the luminescent centre with 'v' as applied voltage.

5.2.2 RELATION BETWEEN BRIGHTNESS AND FREQUENCY

The EL brightness is found to be a function not only of the applied voltage, but also of the frequency. Various relations between brightness and frequency given by different workers are given below.

Curie$^{(28, 29)}$ has derived an expression on the assumption that, there exists a bimolecular proess of recombination of electrons with recombination centres, and that the same number of excited centres are produced per cycle. The expression is

$$B = B_o \cdot \frac{n_o^2}{\left[1 + \frac{n_o \alpha}{2f}\right]} \quad .. \quad (5.16)$$

where α is the recombination coefficient, 'n_o' the initial concentration of free electrons in the conduction band, 'f' is the freuency of applied field and 'B_o' is proportionality constant.

Tharnton $^{(8)}$, considering the recombination rate as determined from the electrons released from traps and controlled by electric field obtained,

$$B = N_o f \left(1 - e^{-(A/f)} \right) \quad .. \quad (5.17)$$

where 'N_o' is the numbr of excited centres for each half cycle, assumed to be constant.

$A = \int_0^{2\pi} e^{(a\ v\ \sin x)} dx$ with $x = wt.$ is a field dependent, which increases with voltage.

Alfrey and Taylor$^{(27)}$ have given a relation,

$$B = B_o p\ e^{(-p/4f)}\ e^{(c/\sqrt{v})} \quad .. \quad (5.18)$$

where, 'c' is constant, 'v' being the applied voltage and 'p', the rate constant for thermal emptying of traps and is given by,

$$P = S e^{-E/KT} \quad .. \quad (5.19)$$

Here 's' and 'E' represent the freuency factor and trap depths respectively.

Zalm (30) showed that, the light emission during each cycle of the applied voltage is not constant, but is dependent on the frequency of the applied field. He gave a relation,

$$B \propto e^{(-\text{ constant } / \sqrt{v})} \quad .. \quad (5.20)$$

where V = F(f,t),'f' being frequency and 't' the time. Thus, light emitted for a cycle is inversely proportional to 'f' so that the total light emitted per unit time is independent of frequency, which is contrary to the observation.

Zalm considered that, the actual voltage across the EL cell is governed by etxra capacitance and resistance present in the experimental cell. Thus for a series of capacitor of value 'c' and the resistance 'R' of EL cell, the actual voltage across the cell may be given by

$$\text{Voltage} = W R C V_0 / \sqrt{1 + W^2 R^2 C^2} \quad .. \quad (5.21)$$

Where, 'Vo' is the amplitude of the applied voltage to the whole system of capacitor and EL cell. If RC $\gg$ 1/w, the voltage across the cell and consequently the luminous emittance is independent of frequency, while with RC $\ll$ 1/w, the emittance increases more than linearly with the frequency. It is thus possible to describe any frequency dependence with a suitable distribution in RC values of the system.

Johnson, Piper and Williams (31) deduced the birhtness frequency relation by considering both excitation and recombination process. Johnson et al. found —

$$B \propto (1 - a\,(1 - e^{(1\ -1/2f\,\tau_2)}\ e^{(-1/2f\tau_1)})\ ..\qquad (5.22)$$

where 'a' is a constant, 'τ_1' is the relaxation time of the excited electrons returning to empty luminescence centres and τ_2 is the time constant of creation of primary electrons.

Chan and Yu(25) have empirically suggested that, the EL emittance (B) varies with frequency (f) of applied sinusoidal field as

$$B = Bs - Bm \cdot e^{(-f/fc)} \quad ..\qquad (5.23)$$

where 'Bs', 'Bm' and 'fc' are constants ($Bs \neq Bm$). The equation indicates that B approcahes a saturation value Bs when $f \gg fc$ and a linear relation between 'B' and 'f' when $f \ll fc$.

5.2.3 BRIGHTNESS WAVES

The variations in the EL brightness with time, during the applied a.c. voltages are called as 'brightness' waves. Besides it is a graphic indication of phase relationship of light component to the applied voltage on a double beam cathode ray oscilloscope. The shape of the brightness wave depends upon the field intensity, frequency and the direction in which the light output is observed. It also depends on the nature of the activators and the spectral characteristic of the detector (PM tube). The existence of the brightness waves and the fact that its frequency is twice the frequency of applied voltage, were first reported by Destriau(32,33) in year 1937.

In general, a brightness wave exhibits two main or the so called 'primary' peaks during each cycle of the applied voltage, some phosphors, however, show additional much smaller or minor peaks referred to as 'secondary peaks'. The existence of secondary peaks is related to the electrons which recombine with luminescence centres after a delay resulting from trapping (2,34). The prominance of primary peaks than the secondary peaks at the applied voltages suggests that, in the phsophor deeper trap levels are less in number. More over, absence of secondary peak suggests that, the electron traps are located close to the luminescence centres.(23,34,35)

5.2.4 EFFICIENCY OF ELECTROLUMINESCENCE

The luminous efficiency (lumens/watt) of electroluminescence of powdered crystal phosphors embeded in an insulating medium and excited by alternating fields, depends on the quality of the phosphor, the EL cell design and the conditions of excitation.

Lehmann (36) has given an empirical relation for efficiency of an EL phosphor namely,

$$\eta^2 = c^2 . (B/V^4) \qquad .. \qquad (5.24)$$

where 'c' is constant. According to this equation, efficiency increases so long as, the brightness increases faster than the fourth power of the applied voltage. The efficiency is seen to be approximately independent of the frequency of excitation but depends upon, the magnitude of the applied voltage.

The simple calculations of luminescence efficiency 'η', in terms of brightness units (arbitrary), as a function of applied voltage and frequency are possible, using Lehmann's (36) relation, viz.

$$\eta = \frac{B}{W} = \frac{B/f}{av^2 . (K''_0 + b(B/f)^{1/2})} \qquad .. \qquad (5.25)$$

Where, K''_0 , a and b are constants. The values of a and b are to be taken from the work of Schwertz et al. (37) while K''_0 is taken to be unity.

5.3 RESULTS AND DISCUSSION

Electroluminescence has been studied in terms of the dependence of the brightness on the applied A.C. voltage and its frequency. The phenomenon is studied in the voltage range 0 V to 1000V and frequency range 100Hz to 3000Hz

5.3.1 DEPENDENCE OF BRIGHTNESS ON VOLTAGE

Brightness output is recorded at different voltages and frequencies for typical samples. Fig. 5.1 to 5.3 show B vs V graphs for some typical samples, It is observed that, brightness is an increasing function of excitation voltage(38). Similar results have been reported for alkaline earth sulphide phosphors doped with Cu (39), Bi and Pd (23) and Silver(22) and many other phosphor systems(40,41,42). This voltage dependence is understood on the basis of visual observations made, that, initially the number of particles in which EL takes place is small but on increasing the voltage, more and more active regions are exposed to voltage gradient above the threshold level.

From B vs V plots it is observed that, 'B' increases sharply at a particular voltage. This is a threshold voltage. It is different for different phosphor and also depends on the frequency. Threshold voltage decreases with frequency for the given range (upto 8 KHz). The variation in threshold voltage with concentrations of activators is systematic. Threshold voltages for some typical samples at different frequencies are shown in the Table 5.1.

The possible relationship between brightness and voltage is examined by plotting (i) B vs. V, (ii) log B vs $1000/\sqrt{V}$, (iii) log B vs V (iv) log B vs log V (v) log B vs log f.(fig.5.1 to 5.15)

It is observed that, none of these show a definite linearity. However, the plots between log B and log V (fig.5.10 to 5.12) show a linear relation with slight deviations at higher voltage. The linearity between log B and log V suggests that the brightness and voltge follows the relation of the form (eq. 5.10) $B = aV^n$ 'a' and 'n' being constants. The relation is similar to equation (5.10 with $V_o = 0$), similar relation is observed for alkaline earth sulphide phosphors doped with Cu (39), Bi and Pd (23), CaS:Mn phosphor (22), CaS:Ag:Dy phosphor (43), $CaSO_4$:Dy phosphor (38)

Patil M.C. (43) observed, the bending of plots at high voltages. It might be due to one or more reasons among the following -

1] The loss of voltage in conducting electrodes, there by lowering the field strength at high voltages.

2] The traps cannot be emptied as fast as they are filled at high frequency and give rise to space charge scattering and hence an increase in radiation—less transition at higher fields 3] The distribution of applied A.C. voltage in the polycrystalline powder form of phosphors. However the second reason seemsthe most probable one.

5.3.2 BRIGHTNESS WAVES

Fig.(5.16) shows typical brightness wave pattern obtained by varying either voltage or frequency. It is observed that brightness waves exhibit one peak per cycle of the applied votlage.

The light emission from single grain concentrated in certain small spots and these spots emitt brightness waves. This, as given by Waymouth and Bitter. In the present investigation, the spot themselves can be thought of as minute rectifying junction(44).

Some times these peaks are not of the same amplitude. This type of asymmetry was observed by Zalm et al.(21) and by Lawangar et al (23). They have concluded that, this lack of symmetry may be due to the emission of light at the side facing the cathode. It may also be due to self adsorption of light, or due to scattering of light by inter-adjacent layers of powder, or by individual particles.

The brightness wave do not show any secondary peaks. This is indicative that the electron traps are located close to the luminescence centres. The nature of the peak observed is similar to sawtooth nature (fig. 5.16).

5.3.3 DEPENDENCE OF EL BRIGHTNESS ON FREQUENCY

The plots of log B versus log f for some typical samples are shown in the fig.(5.13 to 5.15). It is observed that, brightness increases linearly at lower frequency. At higher frequency brightness increases at a faster rate. At very high frequency saturation of brightness occurs.

This behaviour can be understood on the basis of equation given by Curie viz.

$$B = B_o \frac{n_o^2}{1 + (n_o \cdot \alpha / 2f)} \qquad .. \quad (5.26)$$

where, 'α' is the time constant, 'n_o' is the initial concentration of free electrons in the conduction band, 'f' is the frequency of applied alternating field and 'B_o' is the proportionality constant.

The life time of the excited centre is short, compared to the periodicity of applied voltage at low frquency and the factor becomes large, when compared to. 'f', under these conditions, the equation due curie attains a linear for-m

$$B = B_o n_o f$$

This explains the linear behaviour.

At high frequencies the term $\frac{n_o \alpha}{2f}$ becomes much smaller than unity and the equation (5.15) becomes,

$$B = B_o n_o^2 \quad .. \quad (5.27)$$

This expression is independent of frequency and explains the saturation of EL brightness.

The phenomenon can also be explaind in $CaSO_4$:Mn:Eu phosphor as follows(38);

In present studies, the applied electric field obeys the relation

$$E = E_o \sin f_t \quad .. \quad (5.28)$$

where 'E_o' is the field at t = 0, and 'f' is the frequency of the applied field. The phosphor is exposed twice to the peak value of 'E' in a cycle, emitting two quanta by the luminescence centre per cycle. As the frequency 'f' increases, the numbr of emitting quanta also increases. This should yield linearity between f and B. However, in the present study, the increase of brightness versus frequency is nonlinear. The non linearity has been reported in many phosphor systems at high frequencies, where in the saturation effects set in. In the present system, however, the non linearity observed at high frequencies is not due to the saturation effect but due to rapid increase of brightness than that of 'f'. The rapid increase of brightness is probably due to the ionisation of air between the grains of the phosphors.

5.3.4 EFFECT OF ACTIVATORS ON ELECTROLUMINESCENCE BEHAVIOUR

It may be seen from the figures 5.1 to 5.15 that, for various samples with different concentrations of activators (Mn, Eu), the nature of voltage and frequency dependence of brightness is almost similar. This indicates activators have only the effect of modifies the relative intensities in unsystematic way. Similar results are obtained by Mulla(38) for $CaSO_4$:Dy:Bi phosphor, Patil M.C.(43) for CaS:As:Dy phosphor, Shahane G.S.(45) for CaS:Mn:Sm phosphor, Joshi V.A.(46) for CaS:Dy, CaS:Gd Phosphor, Sabnis S.S.(47) for $SrSO_4$ phosphor.

5.3.5 MECHANISM OF ELECTROLUMINESCENCE

The threshold voltages are above 150 v in general, indicating moderaterly high electric fields are required for EL emission. Also there is a power law relationship between brightness and voltage. Both these together suggest that, the probable mechanism of EL in these phosphor is likely to be the direct field ionisation of either valence band electrons or impurity centres, where the transfer of electrons into the conduction band takes place by quantum mechanical tunnelling.(22,48)

5.3.6 KINETICS INVOLVED IN THE EL PROCESS

In the present investigation, the existance of power law relationship between the brightness and voltage indicates bimolecular process in recombination of electrons with luminescence centres(22). Also the variation of brightness with frequency in accordance with the equation (eq.5.16) also points the bimolecular process.

5.4 SUMMARY

The important features of this chapter can be summarised as:

1] The EL brightness B and voltage V follows the power law relation,

$$B = av^n$$ over a wide range of voltage.

2] Activators (Mn, Eu) do not seem to produce significant effect on EL behaviour of phosphors, but they modify the relative intensities only.

3] At lower frequencies the brightness increases with frequency, almost linearly, while at high frequency brightness saturates.

4] The nature of the brightness wave observed is similar to saw tooth nature, producing only primary peak, while no secondary peak is observed.

5] The probable mechanism of EL in these phosphors is likely to be direct field ionisation of either valence band electron or impurity centres, where the transfer of electrons into conduction band takes place by quantum mechanical tunneling process.

6] Kinetics involved in EL process is likely to be bimolecular.

TABLE 5.1

Thereshold Voltages for different samples at different frequencies

Sample No.	Description	Frequency (KHz)	Threshold Voltage (V)
PD 15	$CaSO_4:Mn_{0.1}:Eu_{.01}$	3	430
		5	310
		8	105
PD 16	$CaSO_4:Mn_{0.1}:Eu_{0.05}$	3	275
		5	155
		8	140
PD 17	$CaSO_4:Mn_{0.1}:Eu_{0.2}$	3	225
		5	205
		8	195
PD 19	$CaSO_4:Mn_{0.1}:Eu_1$	3	255
		5	200
		8	195
PD 4	$CaSO_4:Eu_{0.1}$	3	315
		5	295
		8	250
PD 21	$CaSO_4:Mn_{.05}:Eu_{0.1}$	3	290
		5	250
		8	200
PD 12	$CaSO_4:Mn_{0.1}:Eu_{0.1}$	3	300
		5	255
		8	160

TABLE 5.2

Values of 'n' for different samples at different frequencies.

Sample no.	Description	Frequency KHz	n
PD 15	$CaSO_4:Mn_{0.1}:Eu_{0.01}$	3	6.4
		5	4.86
		8	2.69
PD 16	$CaSO_4:Mn_{0.1}:Eu_{0.05}$	3	5.9
		5	5.26
		8	4.7
PD 17	$CaSO_4:Mn_{0.1}:Eu_{0.2}$	3	7.1
		5	12.77
		8	10.0
PD 19	$CaSO_4:Mn_{0.1}:Eu_1$	3	5.38
		5	4.76
		8	6.1
PD 4	$CaSO_4:Eu_{0.1}$	3	6.95
		5	8
		8	6.84
PD 21	$CaSO_4:Mn_{0.05}:Eu_{0.1}$	3	4.54
		5	6.25
		8	13.0
PD 12	$CaSO_4:Mn_{0.1}:Eu_{0.1}$	3	5.22
		5	7.6
		8	5.31

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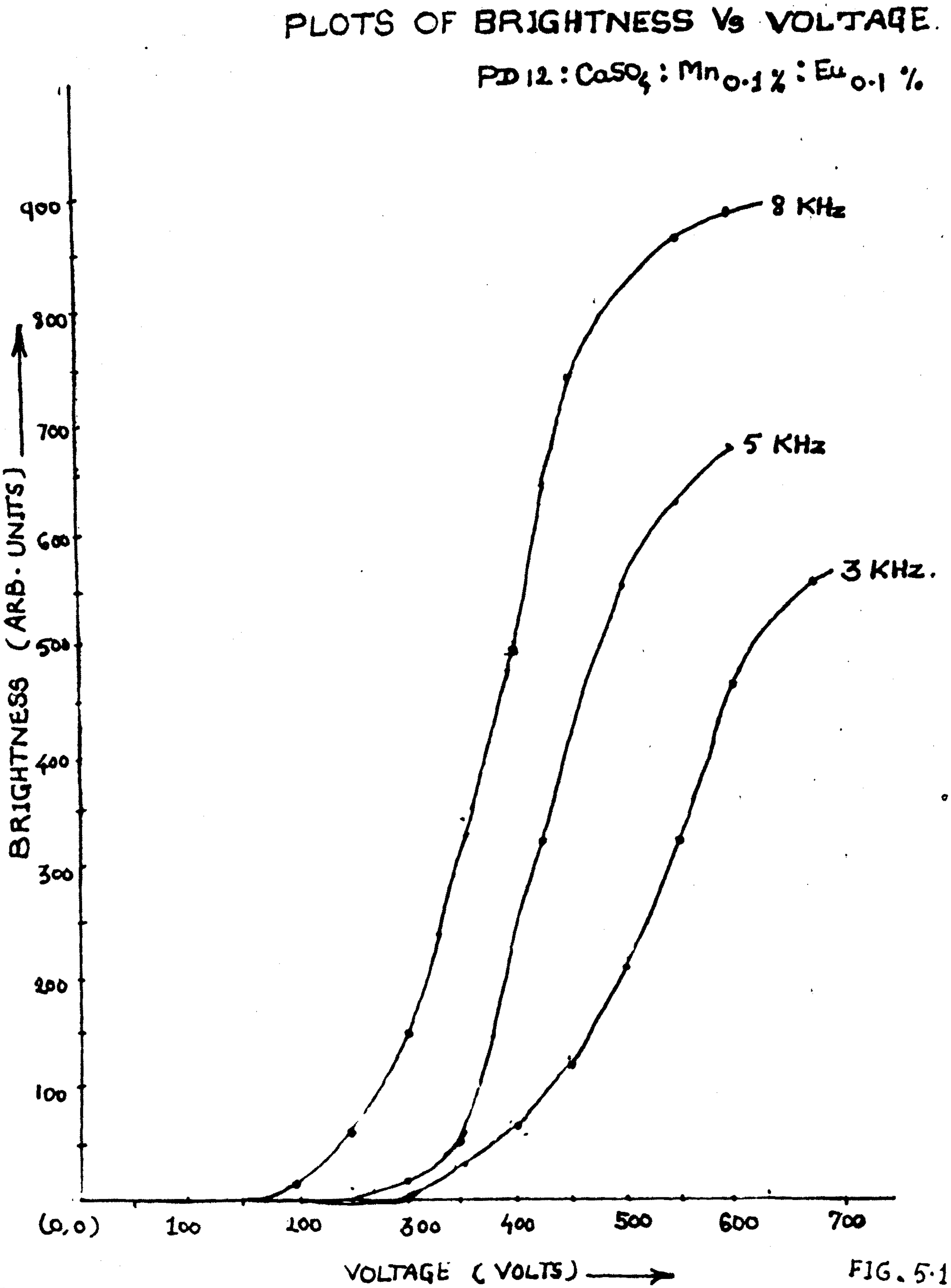


PLOTS OF BRIGHTNESS Vs VOLTAGE.

PD12 : $CaSO_4$: $Mn_{0.1\%}$: $Eu_{0.1\%}$

FIG. 5·1

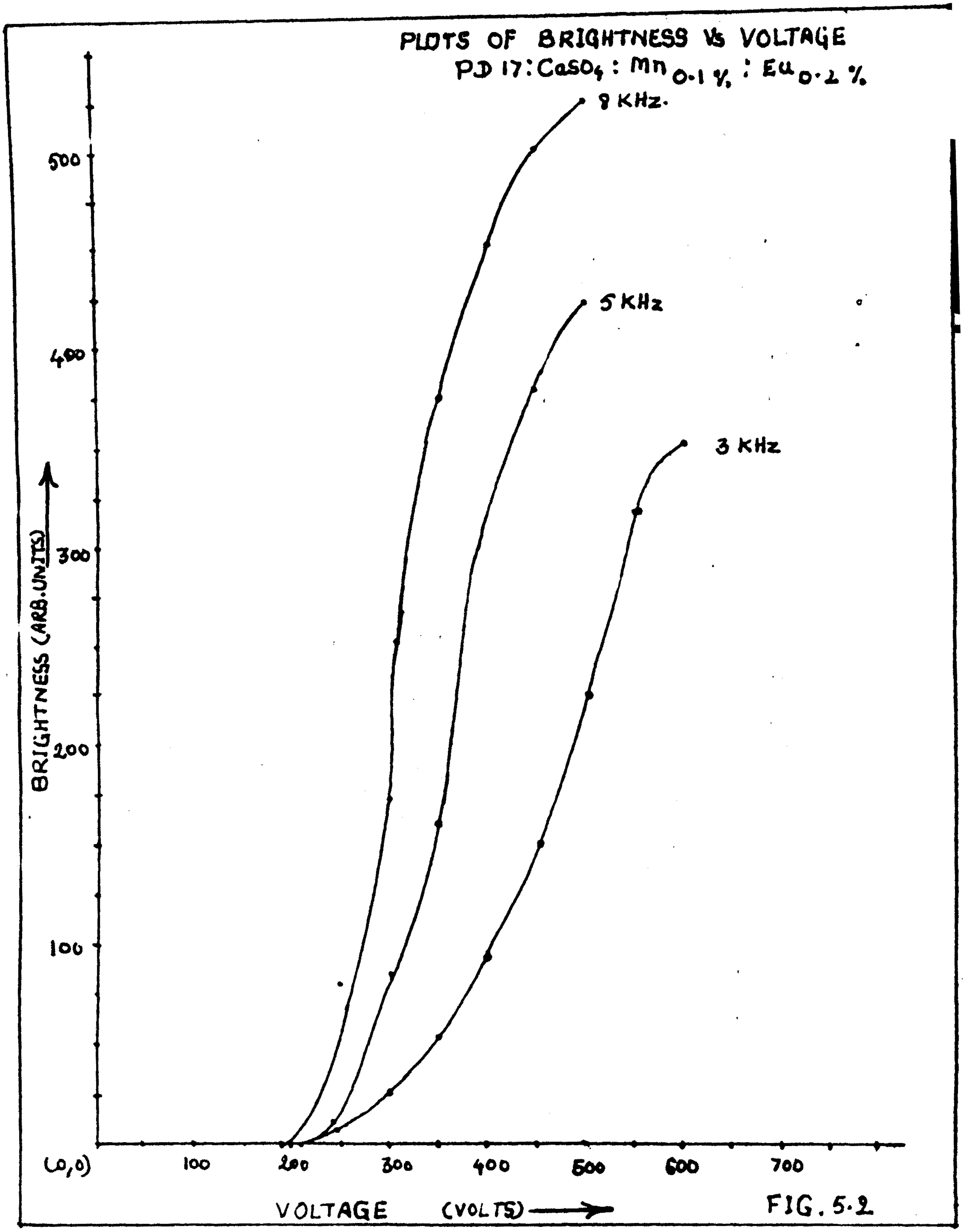

PLOTS OF BRIGHTNESS Vs VOLTAGE
PD 17: CaSO$_4$: Mn$_{0.1\%}$: Eu$_{0.2\%}$
8 KHz.
5 KHz
3 KHz
BRIGHTNESS (ARB. UNITS)
500
400
300
200
100
(0,0)
100
200
300
400
500
600
700
VOLTAGE (VOLTS)

FIG. 5.2

PLOTS OF BRIGHTNESS Vs VOLTAGE

PD21 : $CaSO_4$: $Mn_{0.05\%}$: $Eu_{0.1\%}$

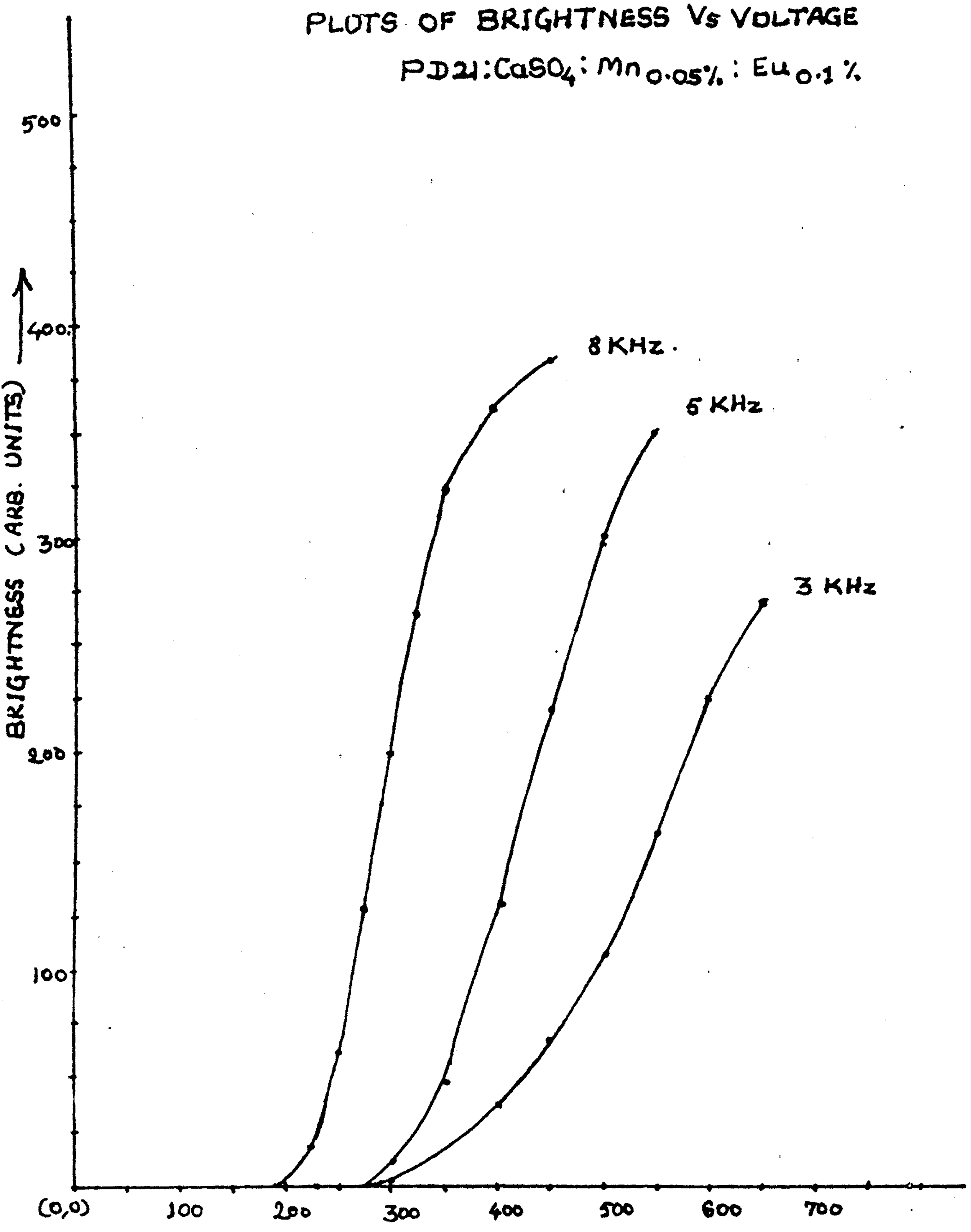


FIG. 5·3

F LOTS OF Log B Vs $\frac{1000}{\sqrt{V}}$

PD 12 : $CaSO_4 : Mn_{0.1\%} : Eu_{0.1\%}$

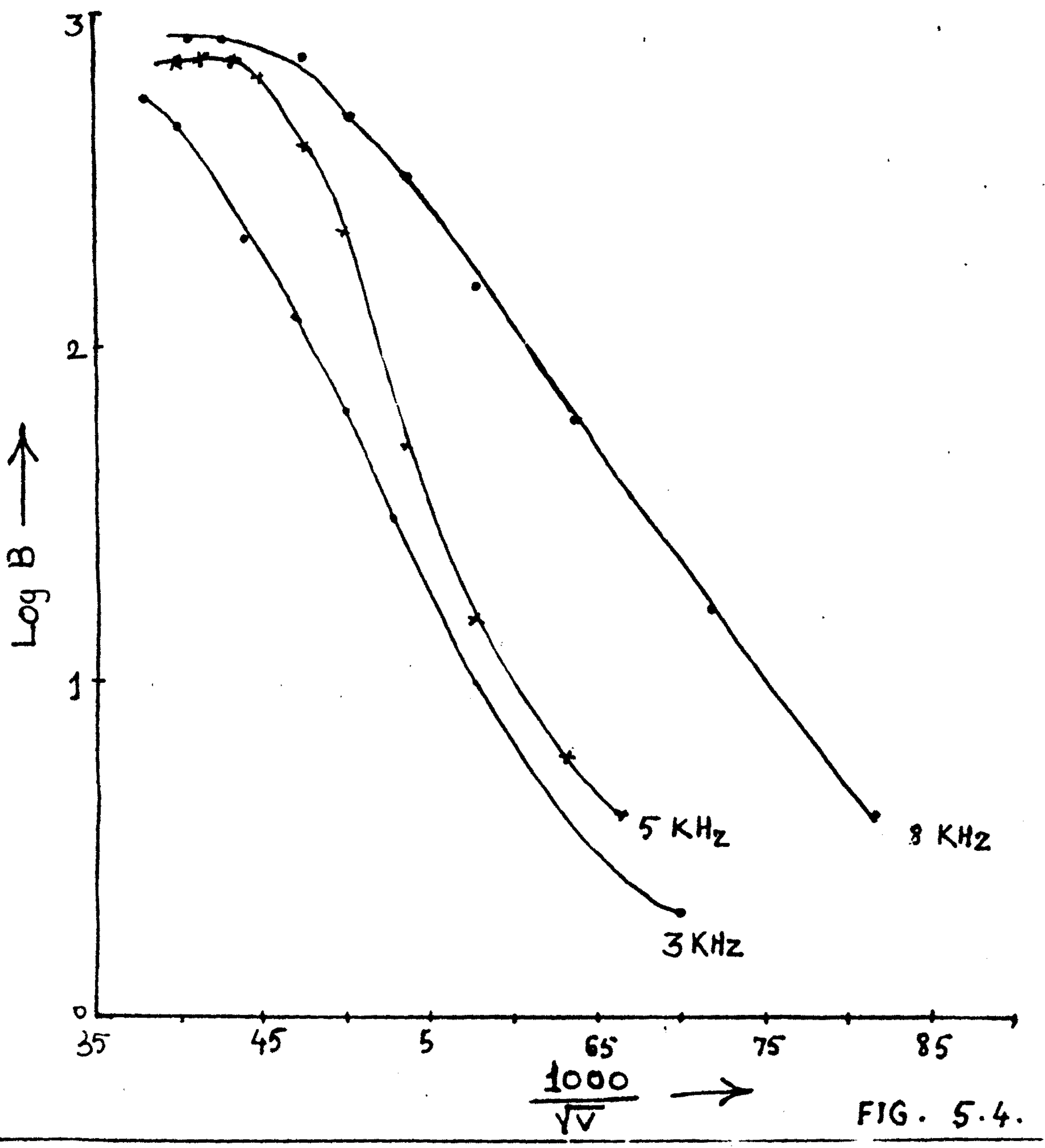


FIG. 5.4.

PLOTS OF Log B Vs $\frac{1000}{\sqrt{V}}$

PD 17 : $CaSO_4 : Mn_{0.1\%} : Eu_{0.2\%}$

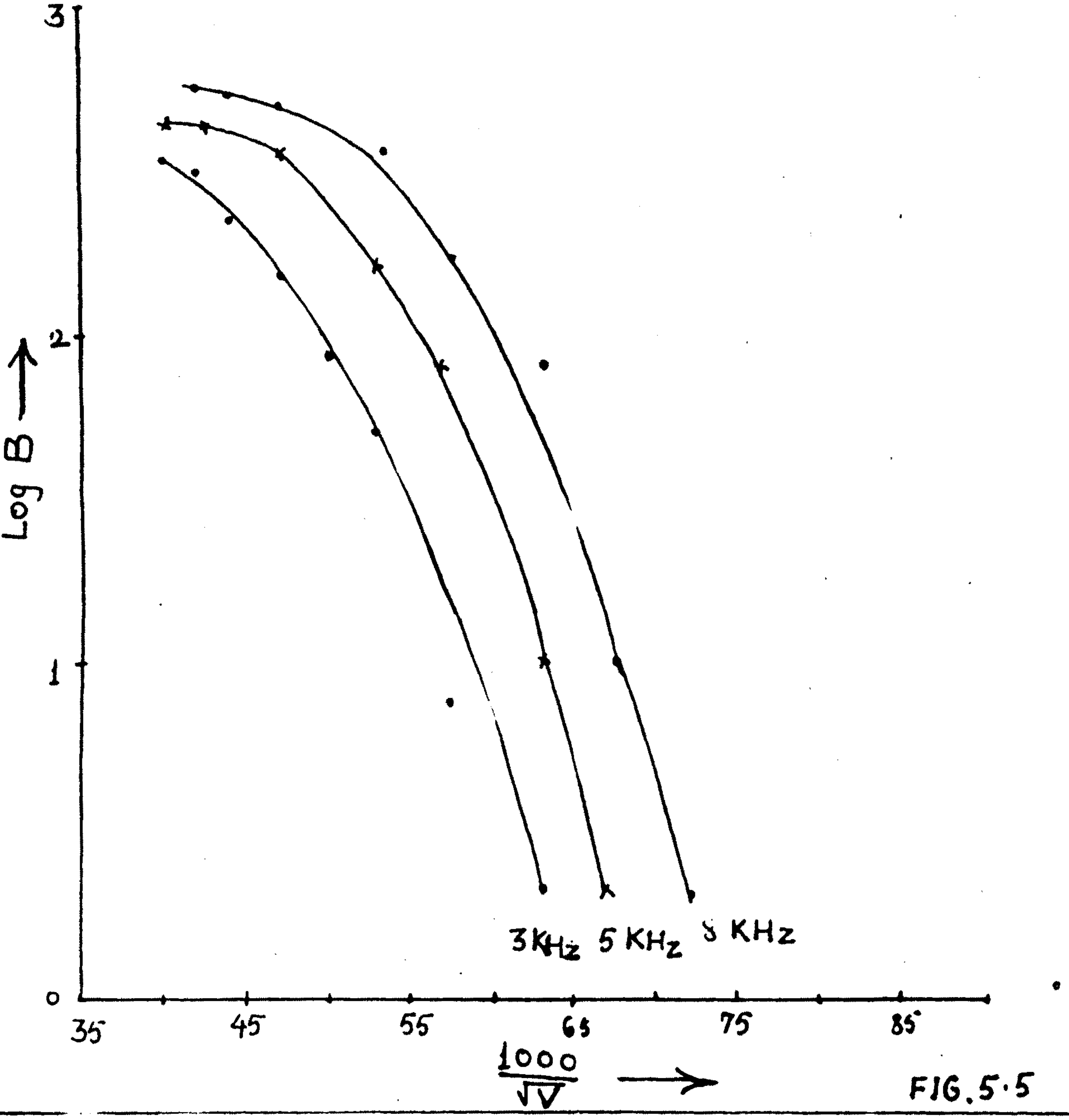


FIG.5·5

PLOTS LOG B Vs $\frac{1000}{\sqrt{V}}$

PD21 : $CaSO_4$: $Mn_{0.05\%}$: $Eu_{0.1\%}$

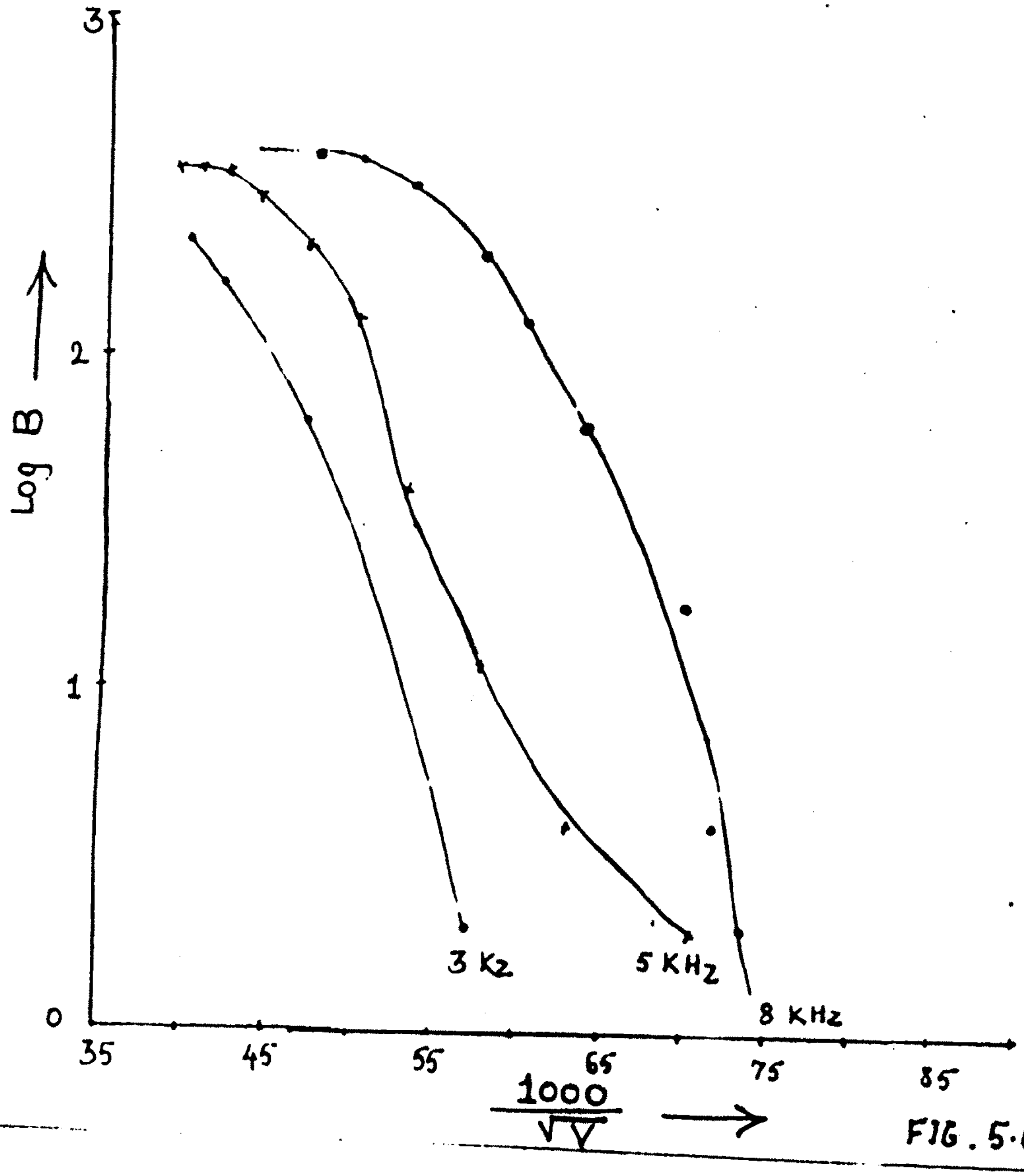
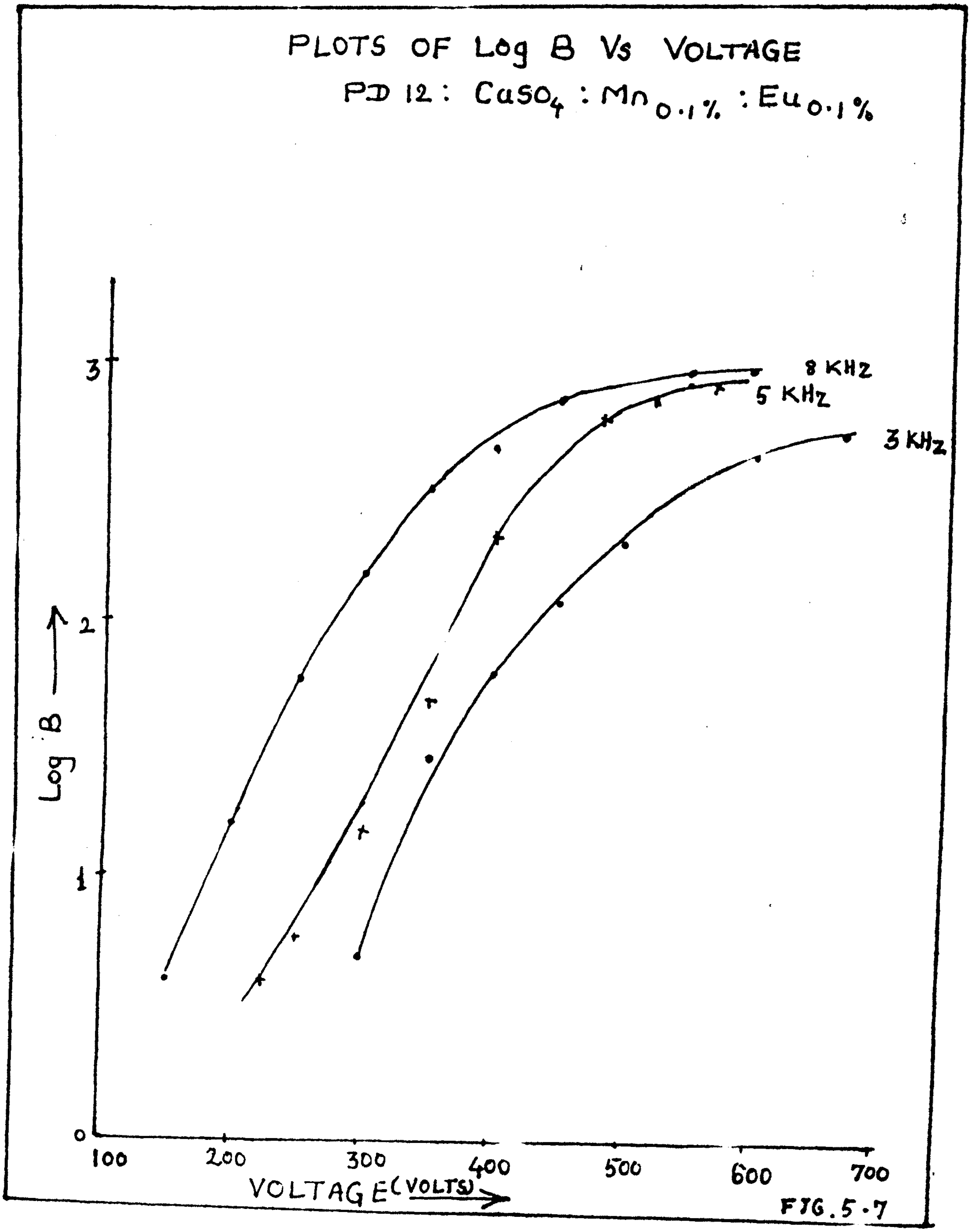


FIG. 5.6.



PLOTS OF Log B Vs VOLTAGE

PD 12 : $CaSO_4 : Mn_{0.1\%} : Eu_{0.1\%}$

FIG. 5·7

PLOTS OF Log B Vs VOLTAGE

PD 17 : $CaSO_4$: $Mn_{0.1\%}$: $Eu_{0.2\%}$

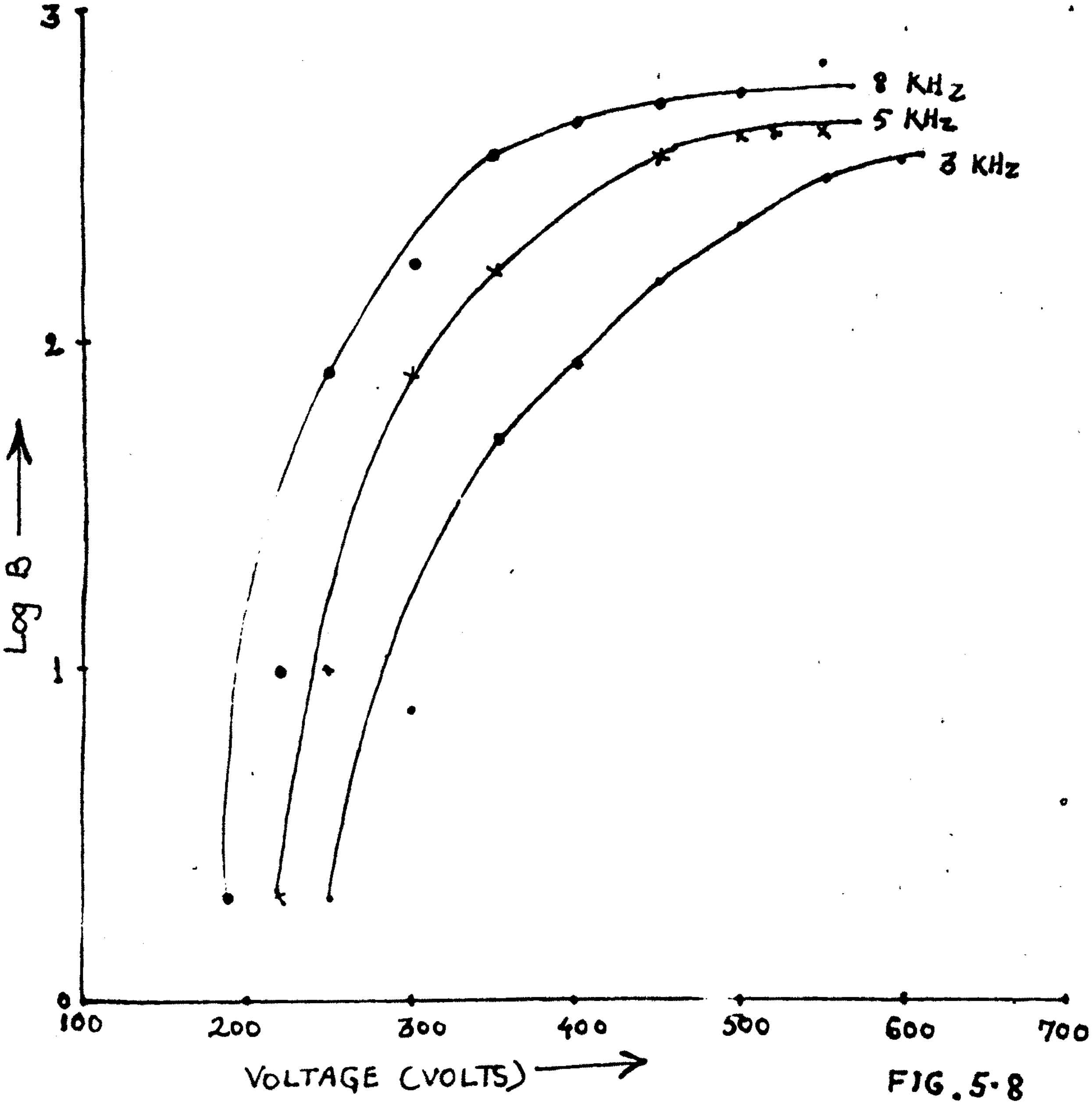


FIG. 5·8

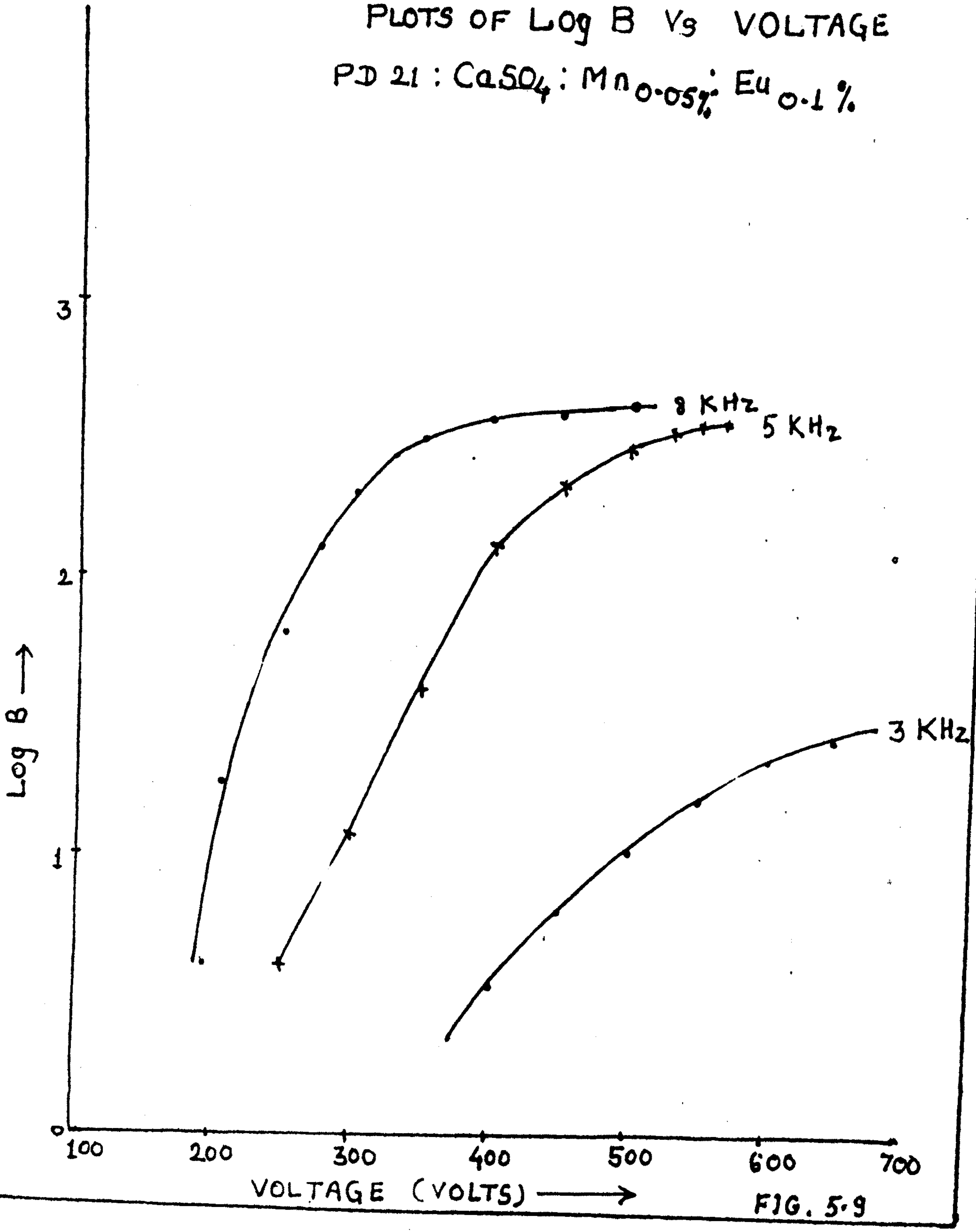

PLOTS OF Log B Vs VOLTAGE
PD 21 : CaSO4 : Mn 0.05% : Eu 0.1%
8 KHz
5 KHz
3 KHz
Log B →
0
1
2
3
100
200
300
400
500
600
700
VOLTAGE (VOLTS) →

FIG. 5.9

PLOTS OF Log B Vs Log V

PD 12 $CaSO_4$: $Mn_{0.1\%}$: $Eu_{0.1\%}$

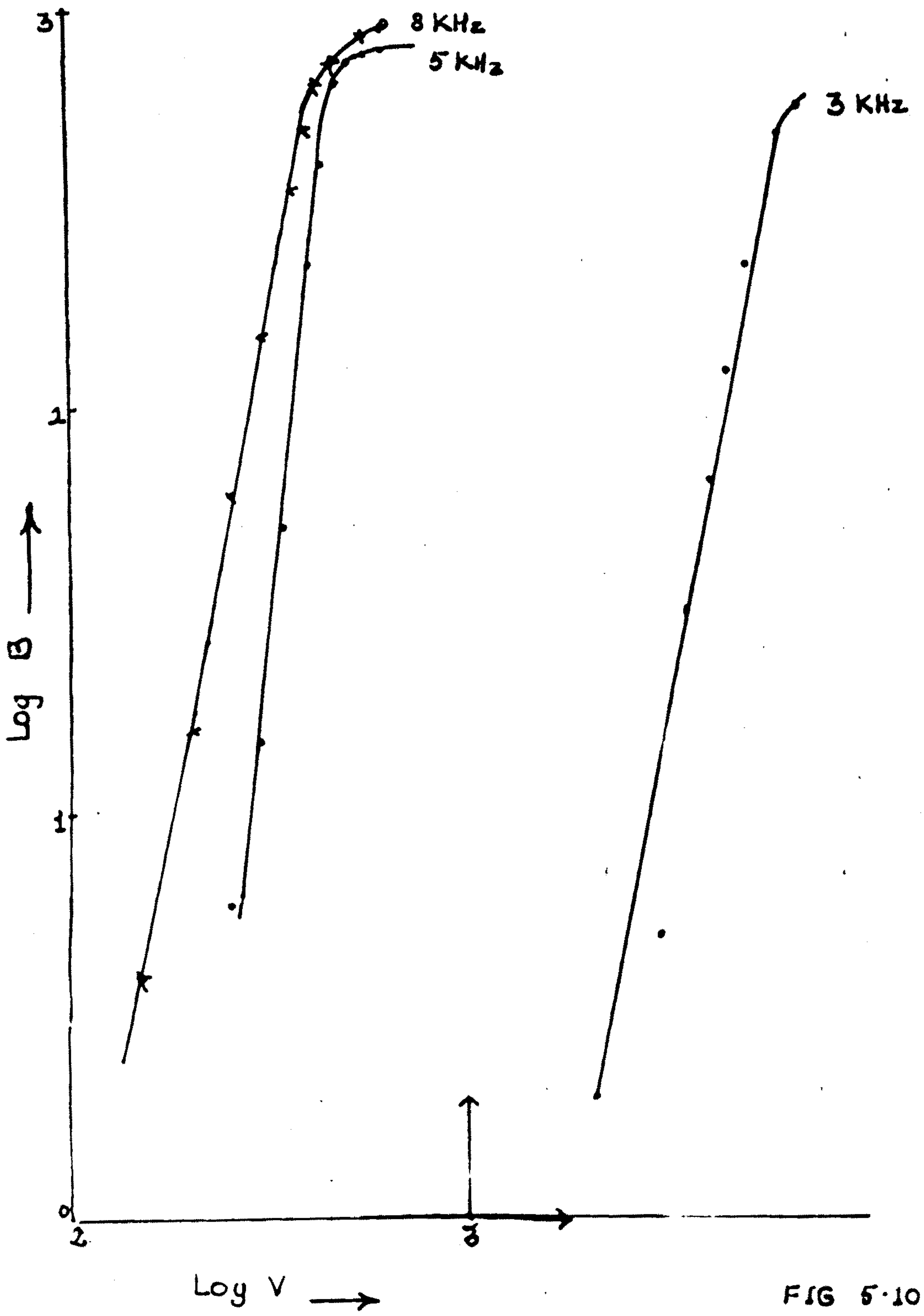


FIG 5·10

PLOTS OF Log B Vs Log V

PD 17 $CuSO_4$: $Mn_{0.1\%}$: $Eu_{0.2\%}$

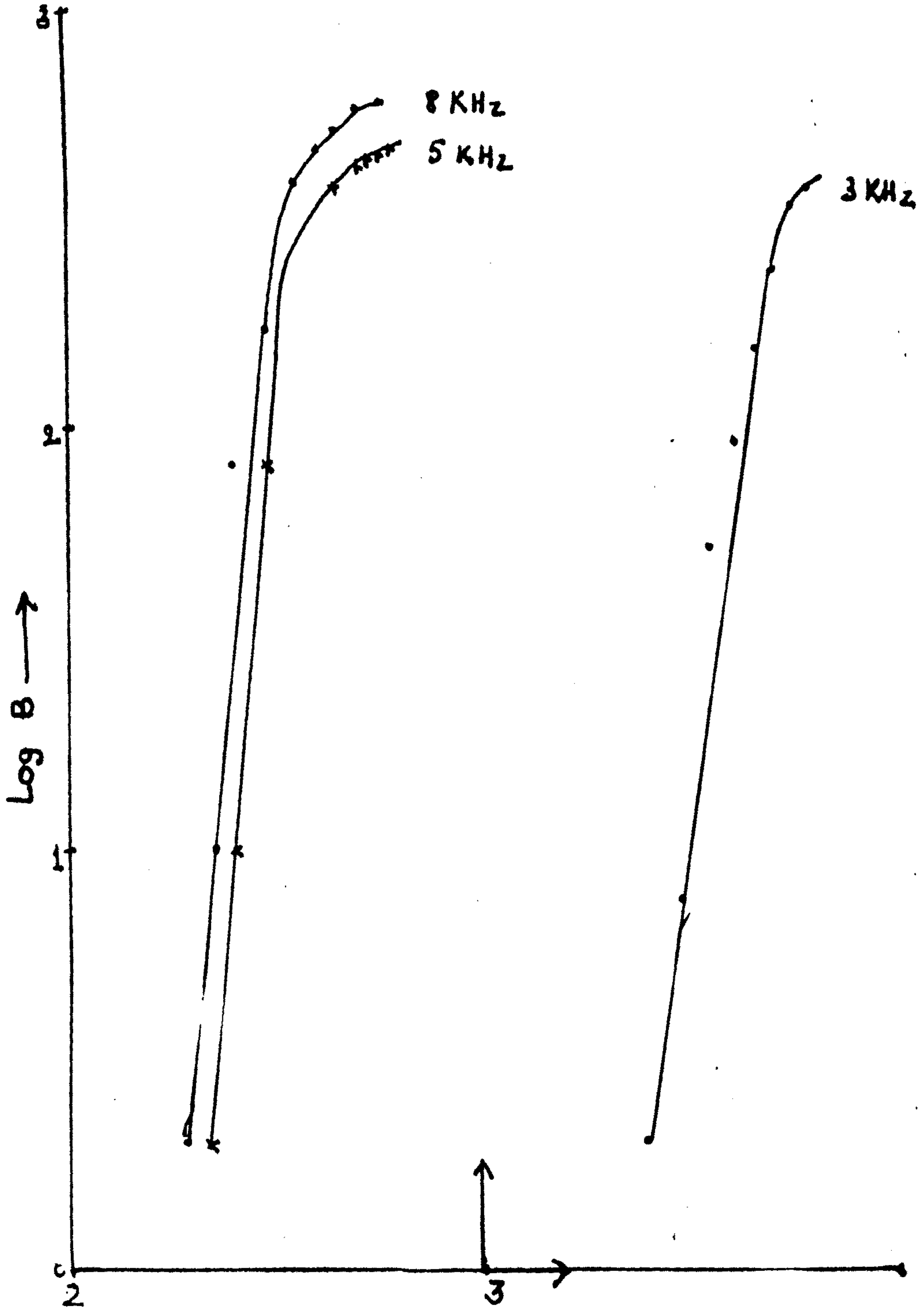


FIG. 5.11

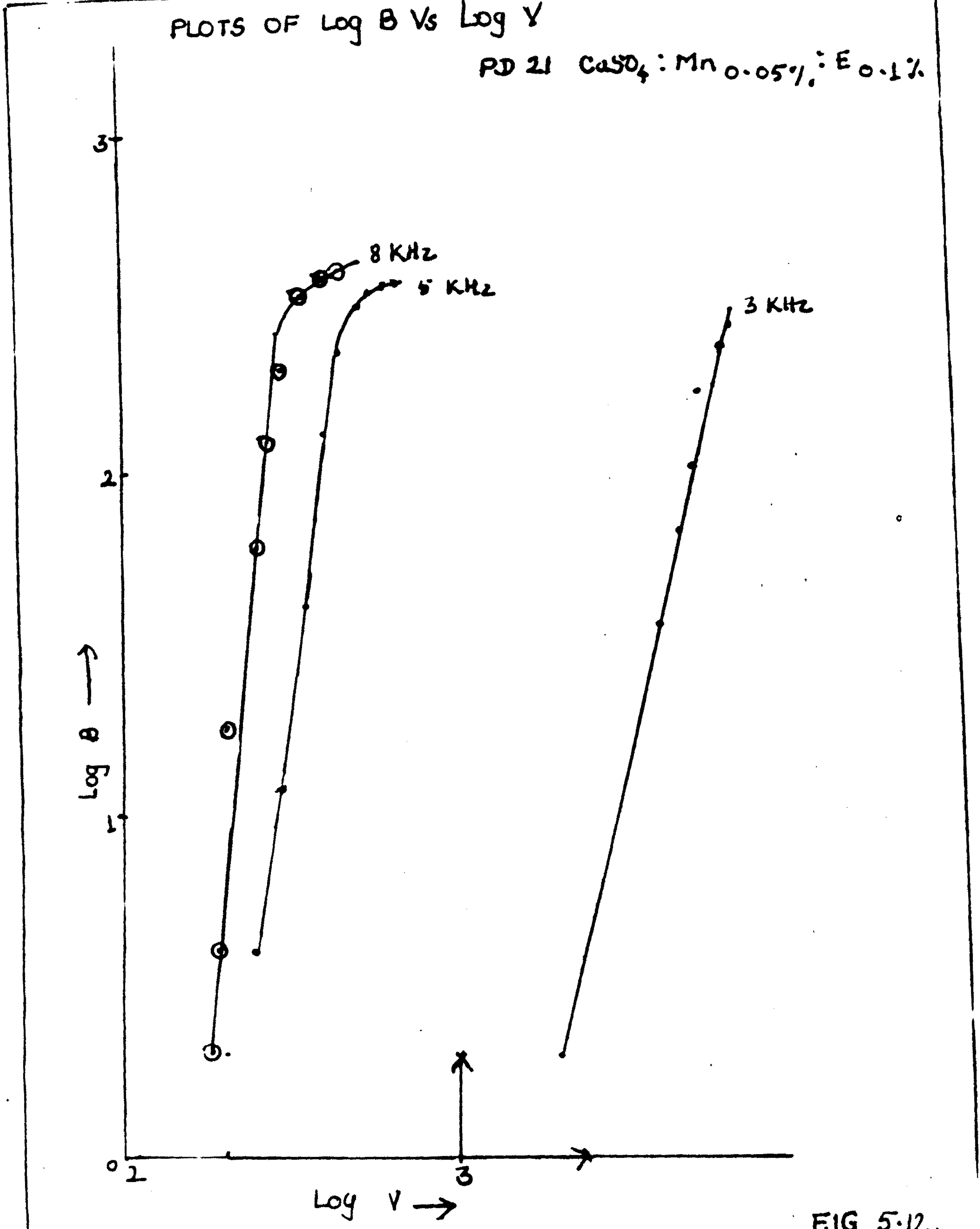

PLOTS OF Log B Vs Log V
PD 21 $CaSO_4$: $Mn_{0.05\%}$: $E_{0.1\%}$
3
2
1
0
Log B
2
3
Log V
8 KHz
5 KHz
3 KHz

FIG 5·12.

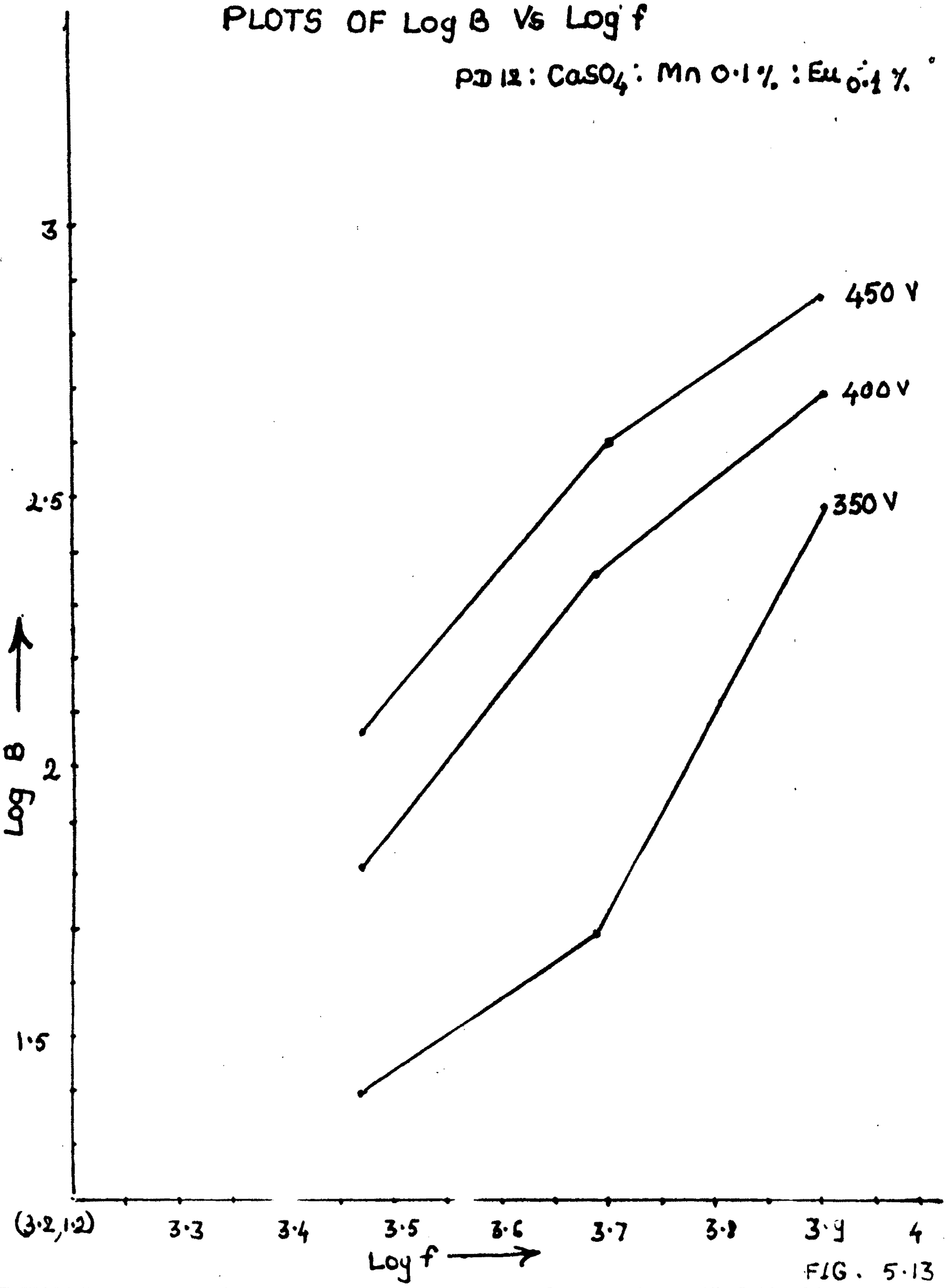

PLOTS OF Log B Vs Log f
PD 12 : CaSO4 : Mn 0·1 % : Eu 0·1 %
450 V
400 V
350 V
Log B
3
2·5
2
1·5
(3·2, 1·2)
3·3
3·4
3·5
3·6
3·7
3·8
3·9
4
Log f

FIG. 5·13

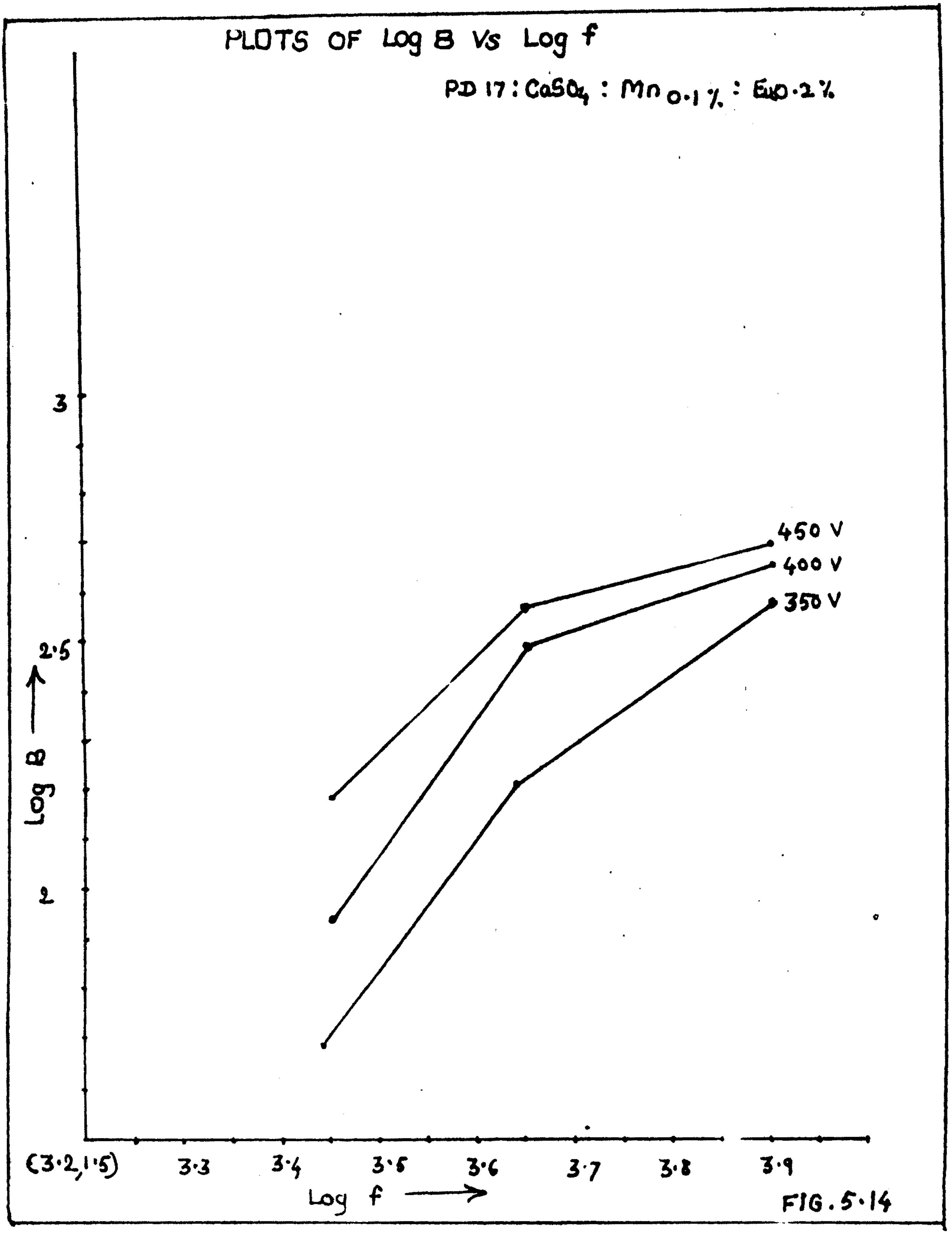

PLOTS OF Log B Vs Log f
PD 17 : CaSO4 : Mn 0.1% : Eu 0.2%
3
2.5
2
Log B →
(3.2, 1.5)
3.3
3.4
3.5
3.6
3.7
3.8
3.9
Log f →
450 V
400 V
350 V

FIG. 5.14

PLOTS OF Log B Vs Log f

PD21 : $CaSO_4$: $Mn_{0.05\%}$: $Eu_{0.1\%}$

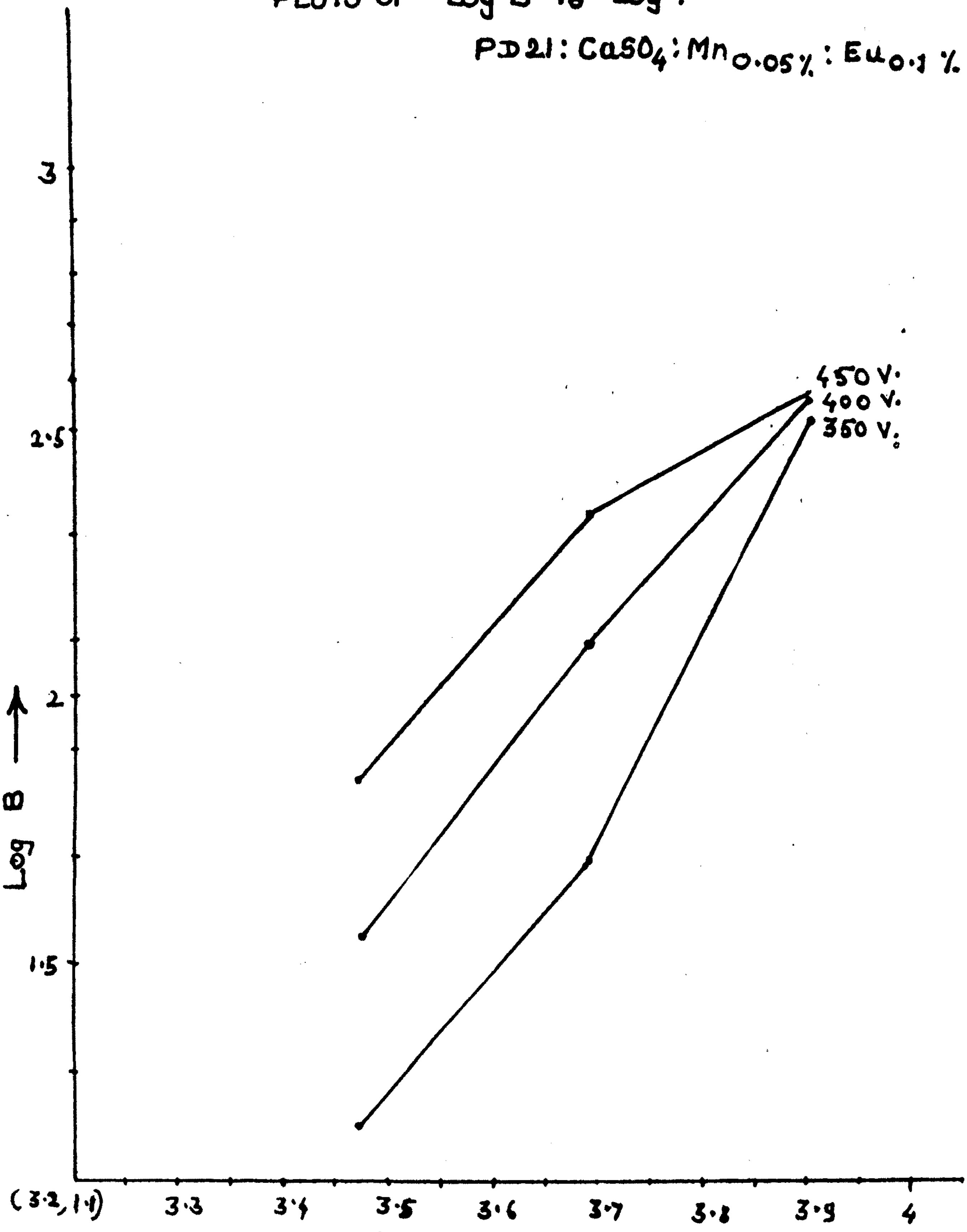


FIG 5.15

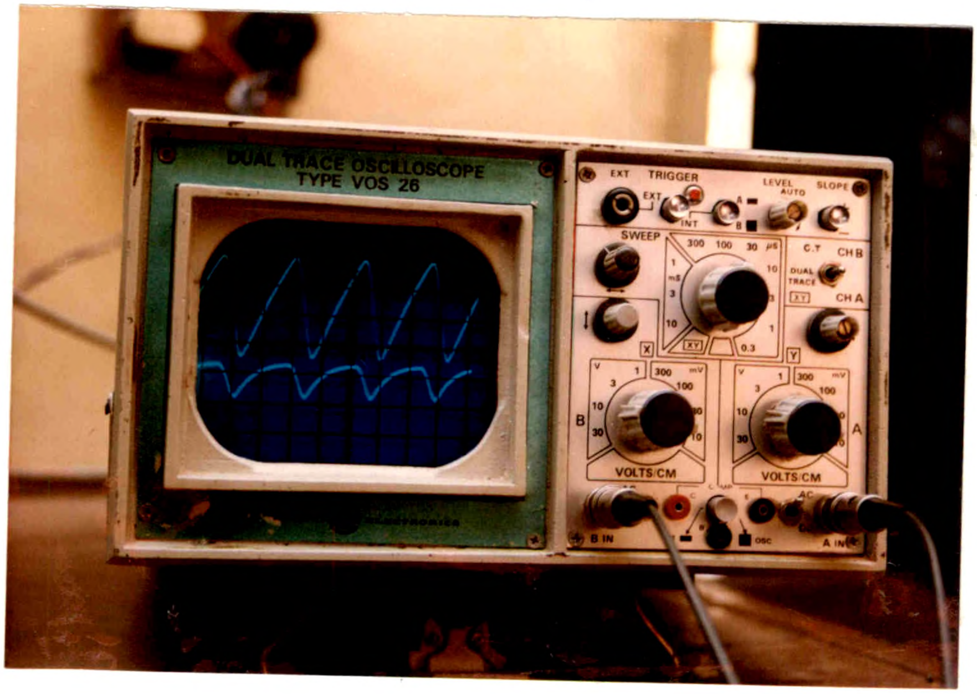


FIG. 5·16 BRIGHTNESS WAVES.