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THE 200-MeV TRANSPORT LINE AND DEBUNCHER

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PURPOSE

To consider the possibility of the use of a debuncher in the linac-booster transport line to cope with the longitudinal beam blow-up at high intensity.

SUMMARY

To design properly a debuncher system and to guess its efficiency, it is necessary to provide information about the beam shape just before the debunching process takes place. The shape of the beam depends: (i) on the initial shape the beam has when it comes out of the linac, (ii) on the focusing and dispersive properties of the transport line, and (iii) on the intensity of the beam.

In this paper we report the results of a run of the program TRANSPORT, modified to include the space charge forces, simulating the transport of the beam from the linac to the booster. Then, a debuncher system is analyzed.

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THE ELLIPSOID AND INITIAL CONDITION

The beam is supposed to have the shape of an ellipsoid in the 6-dimensional phase-space of coordinates x, x', y, y', z, δ. Here x, x', y, y' are the transverse coordinates and angles, z is the longitudinal elongation, and δ the relative momentum deviation, all measured from the center of the ellipsoid.

It is supposed that the beam conserves the shape of an ellipsoid during all the motion in the transport line, although the sizes of the ellipsoid will change.

The initial beam configuration is that of an upright ellipsoid with the following sizes:

x - half size = 1.0 cm
x' - half size = 2.092 mrad
y - half size = 0.5 cm
y' - half size = 2.463 mrad
z - half size = 2.5 cm
δ - half size = 0.1 percent

This configuration is supposed to be independent of the beam intensity, and to be close to that the linac can provide in practice.

During the motion, the ellipsoid will not conserve the upright configuration, especially in the longitudinal phase-plane (z,δ). The ellipse resulting by projection of the ellipsoid on the longitudinal phase-plane has the following equation:

$$\left(\frac{\Delta p}{p}\right)^2 z^2 - 2rL\left(\frac{\Delta p}{p}\right) z\delta + L^2\delta^2 = L^2\left(\frac{\Delta p}{p}\right)^2 (1-r^2). \qquad (1)$$

$\left(\frac{\Delta p}{p}\right)$ is half of the momentum extension in percent, L is half of the beam length and r is the correlation factor which measures the rotation of the ellipse with respect to the axis.

THE TRANSPORT LINE

Since our main goal was to investigate the beam blow-up caused by the space charge, we replaced the actual transport line with a more simplified model. This has 23 identical cells of structure FODO. The quadrupoles are 0.3 m long and separated from each other by 1 meter. The length of a single cell is thus 2.6 m. The total length of this line is close to the length of the actual line: 60 m. Every quadrupole has (±)2 kG on the surface of the poles and a full aperture of 8 cm.

In this way we neglected the dispersion introduced by the bending magnets and assume that the action of the space charge is independent of the lattice system.

The initial shape of the beam as described previously is matched to the particular transport model we are using here.

THE SPACE CHARGE FORCE

The space charge force is calculated assuming: (i) the beam remains in free space, and (ii) that the particles are uniformly distributed in the ellipsoid.[1]

At 5 cm intervals, a particle receives a tridimensional kick which simulates the space charge forces. The kick is a function of the particle location in the ellipsoid and of the intensity.

RESULTS OF THE CALCULATIONS

These results are shown in Fig. 1, 2 and 3, which, respectively, give $\frac{\Delta p}{p}$, L and r versus the number of cells crossed, for various intensity values.

Comparison of these results with those obtained previously by S. Ohnuma[2] shows a full agreement, although the models used for the space charge forces are different in the two cases. Besides, it results that the blow-up is independent of the structure of the transport line because the case treated by Ohnuma is the real one.

In the transverse plane, the defocusing action of the space charge introduces a mismatch between the beam and the transport line. As a consequence, the beam sizes increase. We found that, in our model, the horizontal increase is only 3% and the vertical increase is only 4%, at 100 mA. Nevertheless, the transverse increase depends on the structure of the transport line. Calculations made independently by S. Ohnuma and E. Hubbard indicated an increase of 35% in the horizontal plane and of 12% in the vertical plane with the actual transport line, at an intensity of 100 mA.

THE DEBUNCHER

This is a cavity with the voltage drop across the gap

$$V = V_o \sin 2\pi ft.$$

We set at $t = 0$ the instant when the center of the beam crosses the gap. We can replace the time t with the internal coordinate z through the relation $z = \beta ct$, where βc is the beam velocity and c the light velocity. If the bunch is enough short, i.e., if $\frac{2\pi fL}{\beta c} << 1$, we can expand the sine wave and keep only the linear term, namely

$$V \sim V_o \frac{2\pi f}{\beta c} z$$

or in terms of relative momentum deviation

$$\delta = \alpha z \qquad \text{with} \qquad \alpha = 2\pi \frac{V_o f}{\beta^3 cE}$$

where E is the total energy of a particle.

After all the particles have been kicked by the cavity, the shape of the beam in the $(z-\delta)$-plane is still that of an ellipse but with this new equation

$$\left[\alpha^2 L^2 - 2\alpha r\left(\frac{\Delta p}{p}\right) + \left(\frac{\Delta p}{p}\right)^2\right] z^2 + $$
$$+ 2L\left[\alpha L - r\left(\frac{\Delta p}{p}\right)\right] z\delta + L^2\delta^2 = L^2\left(\frac{\Delta p}{p}\right)^2(1-r^2) \qquad (2)$$

which reduces to Eq. (1) for $\alpha = 0$.

The optimum of debunching is achieved when the resulting ellipse is upright, i.e., for

$$V_o = \frac{\beta^3 cE}{2\pi f} r \frac{(\Delta p/p)}{L}. \qquad (3)$$

In this case, Eq. (2) becomes

$$\left(\frac{\Delta p}{p}\right)^2(1-r^2)\ z^2 + L^2\delta^2 = L^2\left(\frac{\Delta p}{p}\right)^2(1-r^2).$$

The bunch length is unchanged but the momentum spread is reduced by a factor $\sqrt{1-r^2}$.

In our case it is $\beta = 0.56616$, $E = 1.138$ GeV and $f = 200$ MHz which gives

$$V_o = 4.93 \quad r \frac{\Delta p/p}{L} \quad 10^9 \text{ V}\cdot\text{cm}, \quad (L \text{ in cm})$$

The quantity $r\frac{\Delta p/p}{L}$ is plotted in Fig. 4 versus the number of cells crossed, for various values of intensity.

The debunching factor, defined as the ratio expressed in percent of the momentum spread after the debuncher to the momentum spread at the beginning of the transport line, is plotted in Fig. 5.

Observe that, as we can see from Eq. (3), the required peak voltage V_o can be halved if we take $f = 400$ MHz. Nevertheless, the condition $\frac{2\pi f}{\beta c}$ L << 1 is no more satisfied, especially at high intensity when the bunch length might correspond even to half of the rf wavelength.

In conclusion, the peak voltage V_o and the debunching factor depend on the location of the debuncher. As we can see from Fig. 4 and 5, the best location is that as close as possible to the booster.

The data relative to two possible locations are tabulated in the table following.

a) Location #1: 42.5 m from the beginning of the line (end of linac tank #9)

Current (mA):	0	50	100
Bunching factor (%):	65	49	40
Peak voltage (MV):	0.9	1.3	1.4

b) Location #2: 53.5 m from the beginning of the line (end of linac tank #9)

Current (mA):	0	50	100
Bunching factor (%):	57	40	31
Peak voltage (MV):	1.0	1.4	1.6

REFERENCES

1. F.J. Sacherer and T.R. Sherwood, "The effect of space charge in beam transport lines." Proceedings of the 1971 Partical Acceleator Conf., Chicago, March 1971, p. 1066.

2. S. Ohnuma, "Do we need a debuncher in the 200-MeV transport system?" NAL Internal Report TM-319, July 1971.

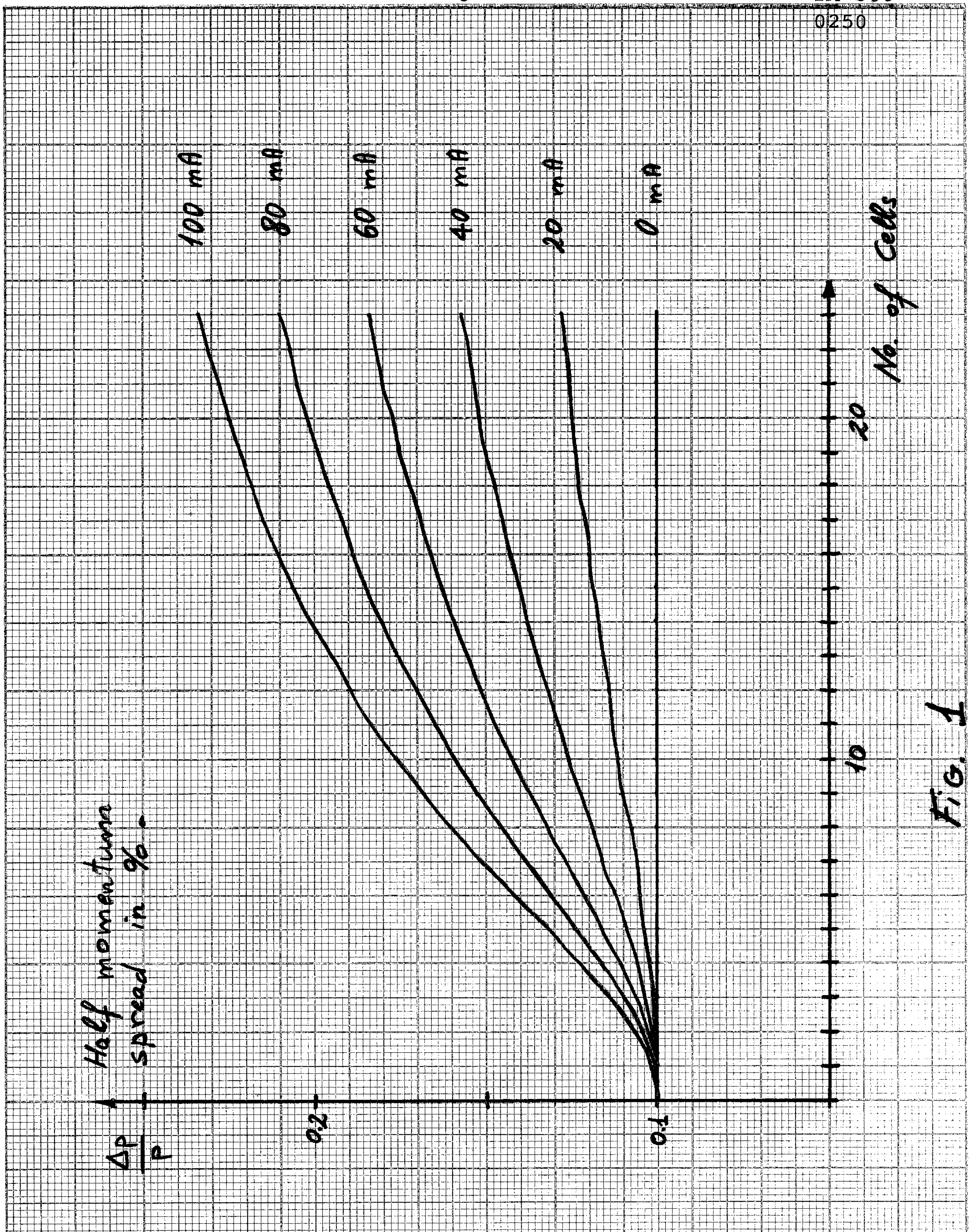
Half momentum spread in %.
$\frac{\Delta p}{p}$
0.2
0.1
100 mA
80 mA
60 mA
40 mA
20 mA
0 mA
10
20
No. of Cells

FIG. 1

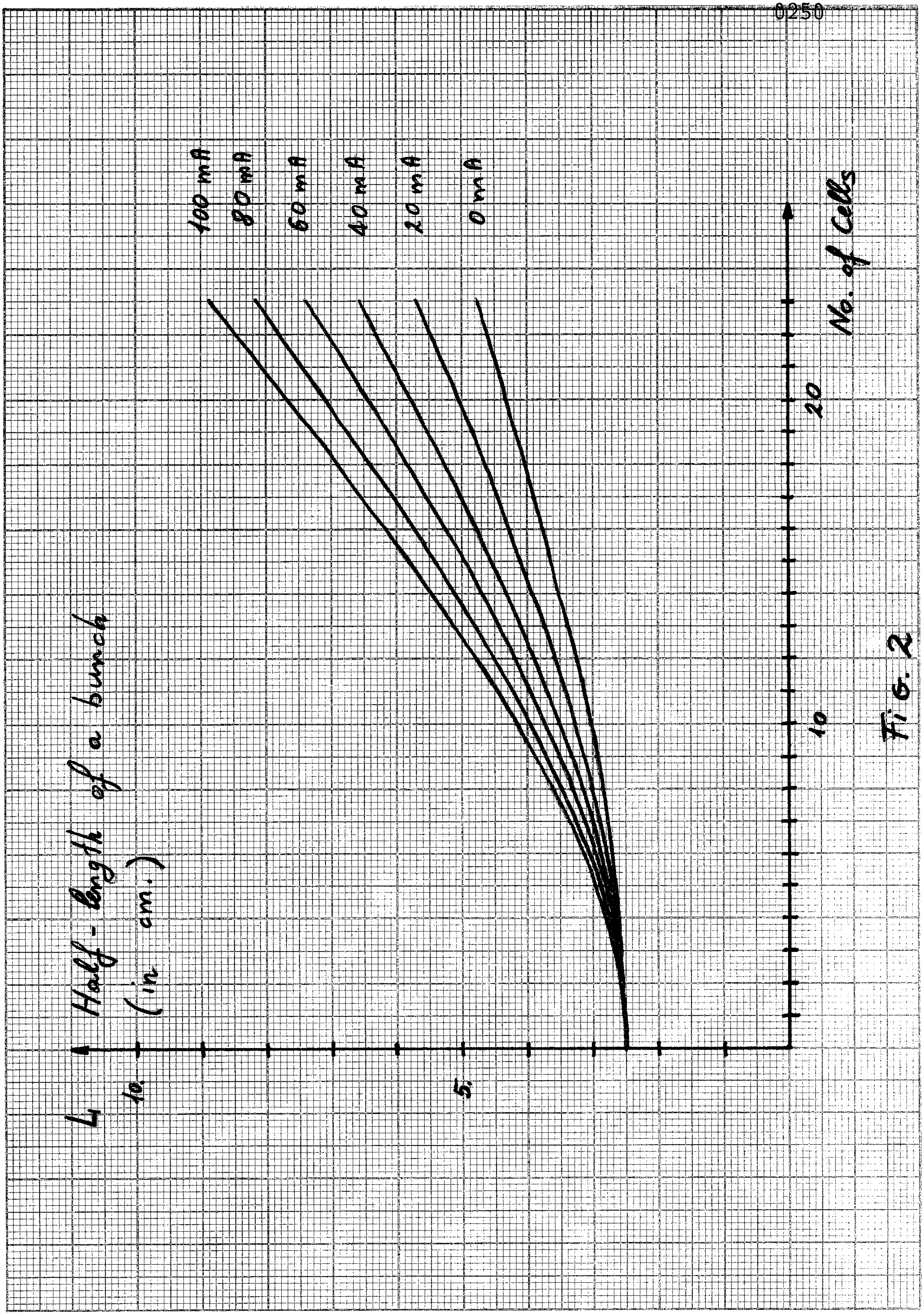
L Half-length of a bunch
(in cm.)
10.
5.
No. of Cells
10
20
100 mA
80 mA
60 mA
40 mA
20 mA
0 mA

FiG. 2

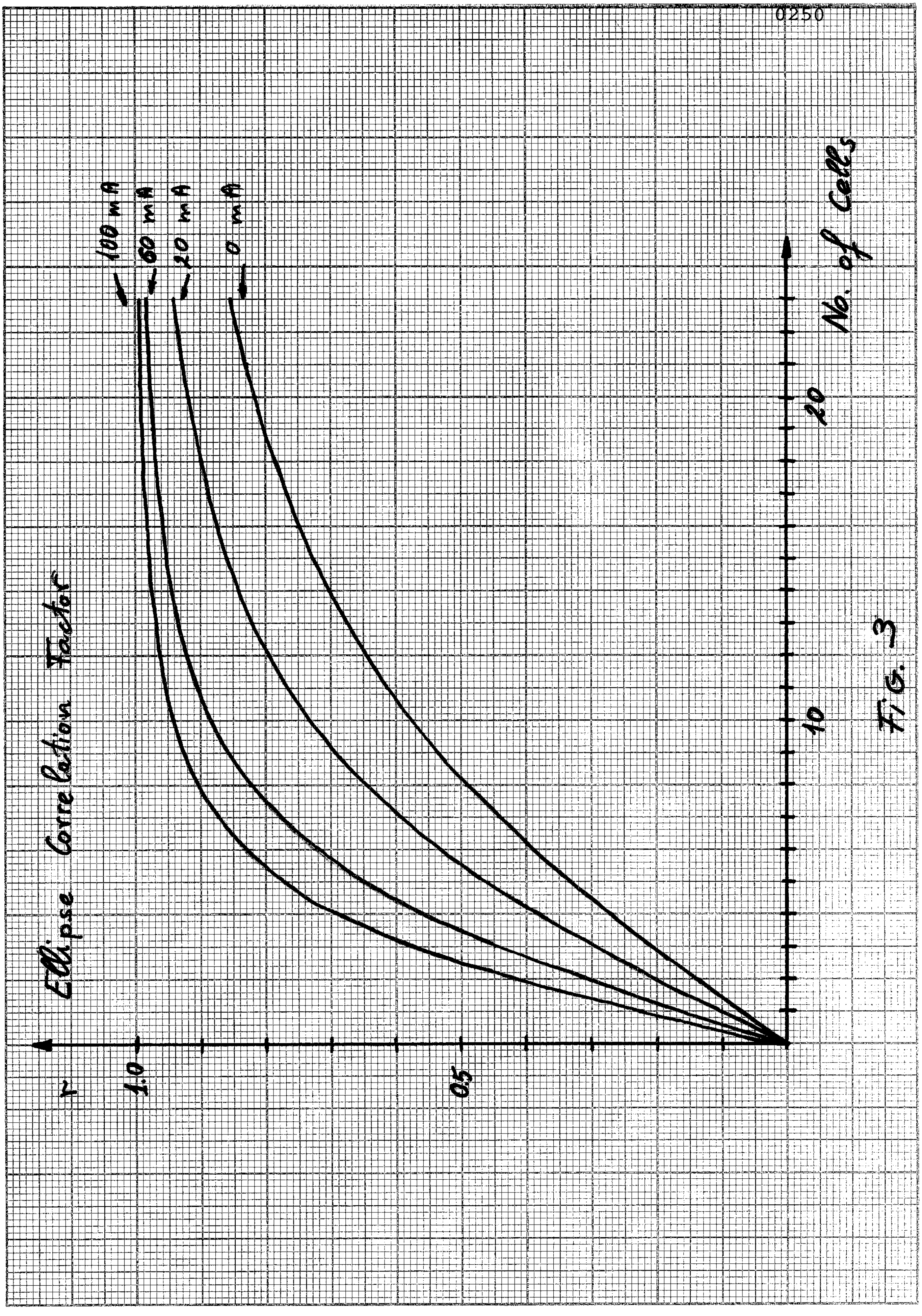
Ellipse Correlation Factor
r
1.0
0.5
100 mA
60 mA
20 mA
0 mA
10
20
No. of Cells

FIG. 3

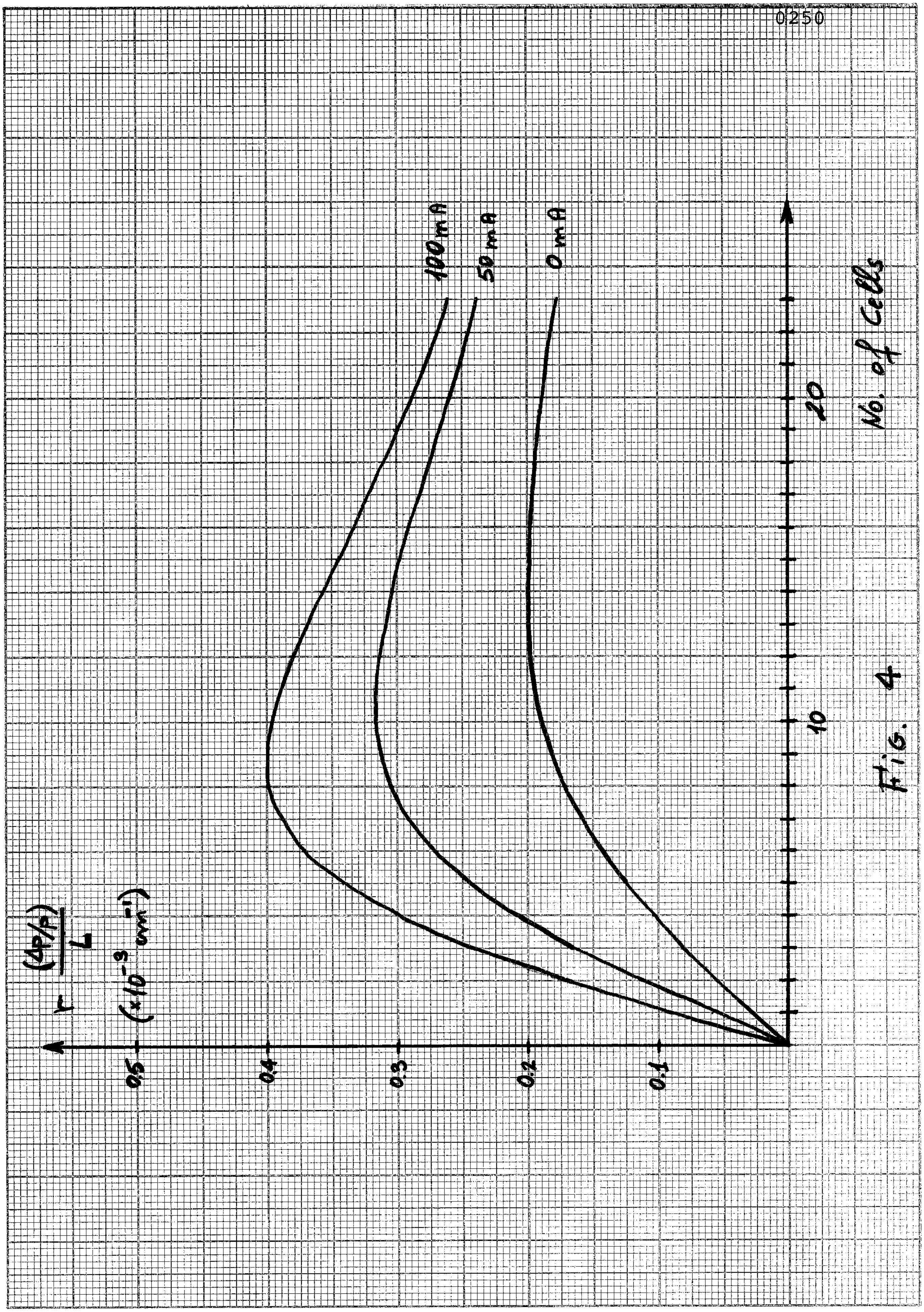
r $\frac{(\Delta p/p)}{L}$
($\times 10^{-3}$ cm^{-1})
0.5
0.4
0.3
0.2
0.1
10
20
No. of Cells
100 mA
50 mA
0 mA

Fig. 4

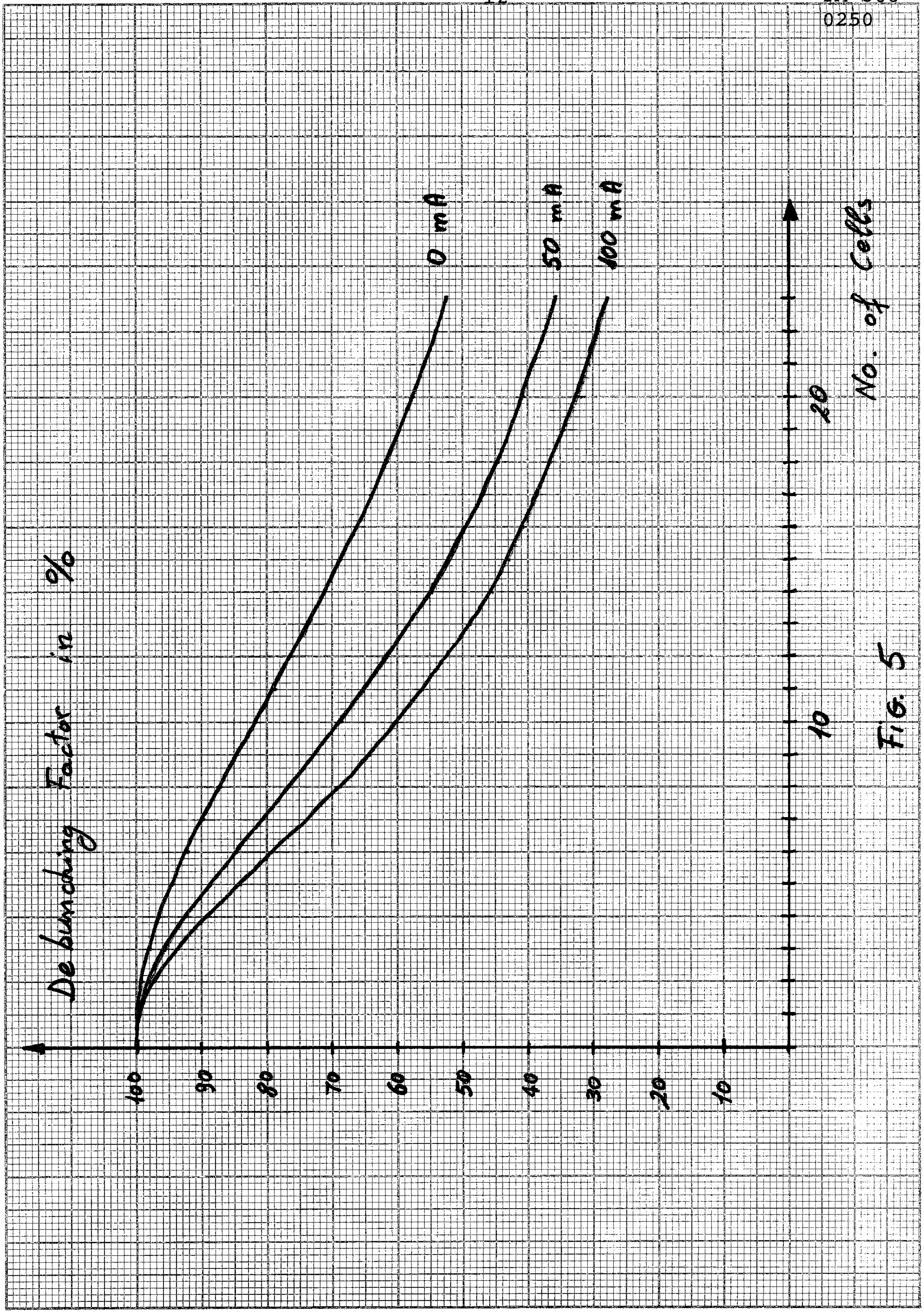
Debunching Factor in %
0 mA
50 mA
100 mA
No. of Cells
100
90
80
70
60
50
40
30
20
10
10
20

Fig. 5