SOME REMARKS ABOUT POLEFACE WINDINGS.

Contents:

1. About possible and impossible corrections.

Fig. 1 gives an idea about the influence of one "poleface bar', in different radial positions, on the field gradient. As would be expected, the effect is greatest in the closed part of the gap.

With a uniform current distribution a nearly linear gradient correction may be achieved (fig. 2; see report MM 19). In this figure "current density" means "current per cm in r-direction".

If a linear correction of the same sign, but with an opposite slope, would be required, a current distribution as illustrated in fig. 3 might be used. This distribution was calculated from similar measurements as illustrated in fig. 1; the value $z = 2$ was taken, because here the irregularities in the slope are much larger than in the median plane. It would be possible to reduce the irregularities by using wires with a smaller diameter. As will be shown later on, this might create other difficulties.

With two sets of windings, giving effects as illustrated in figs. 2 and 3, all gradient corrections, linearly dependent on r, could be produced, including a constant correction across the whole gap. However, for achieving the latter, the current density in the windings as shown in fig. 3 would have to be 7 times as great as in the fig. 2 configuration, due to the fact that most of the windings of fig. 3 are concentrated in the open region of the gap, where they have a small influence on the gradient. As the power dissipation is proportional to the square of the current, the temperature increase of the windings would limit the n-variations obtainable in this way, especially at the open end of the gap, where more than one layer would have to be used.

A simple calculation may illustrate this. Suppose a n-variation as indicated in fig. 3, with a maximum value of 4 o/o at $r = 7$, during the whole acceleration time, would be required. This would mean a current increasing linearly with time, and causing a gradient of 20 gauss/cm at 12000 gauss. The peak current density required (again at 12000 gauss) would be about 550 A/cm between $r = 6$ and $r = 8$ for the winding of fig. 3. If we suppose that the total copper thickness between $r = 6$ and $r = 8$ would be 4 mm, the peak heat development divided by the surface of the windings in contact with the poleface would be 13000 W/m^2 here. The average heat development would be 9 times as small, due to the character of the cycle. This means that a power of 1400 W/m^2 would have to be dissipated. If we suppose the heat conductivity of the insulating material to be 4.10^{-4} joule/cm sec $^\circ$ C, and its thickness 1,5 mm, we find a temperature difference of 50° C, neglecting the heat transport to the air in the gap. It would be inadvisable to increase the copper cross section much; in fact, the eddy current disturbance due to the concentration of windings at the open end would probably be too large with this thickness, unless conductors of a very small width would be used (See appendix 1).

The order of magnitude of the power required for this correction alone would be 50 kW (average), or 450 kW (peak) for the whole machine.

These temperature and power figures make it clear that a change of n of this order of magnitude during the whole accelration cycle cannot easily be produced by the poleface windings.

The same reasoning may be applied to some other corrections, depending on r in a different way. If, for instance, a constant correction across the whole gap would be asked for, this would cause practically the same temperature increase at $r = 7$ as in the case of the fig. 3 correction with the same maximum value, if it would have to be produced by poleface windings alone. If quadrupole lenses would be used for this purpose, the power required would be an order of magnitude smaller, and no temperature difficulties would be experienced. Also, the fig. 3 correction might be produced by energizing the fig. 2 windings in the opposite direction, and shifting the whole n-plateau by means of the quadrupole lenses.

The correction for the saturation effect is easier to obtain, because it is strongest at the closed end, and because the current is only required during a short part of the cycle. If we use 2 mm thick bars, it is possible to compensate for the saturation, using the fig. 2 distribution with a mean power of 4,2 kW and a peak power of 260 kW for the whole machine, supposing the cycle ends at 14 Kgauss. For 12 Kgauss these powers are an order of magnitude smaller. The calculation of these figures is given in appendix 2.

Of course, the saturation effect is not exactly linear with r . Also, the ratio of the slope to the value at $r = 0$ is not exactly the same as in fig. 2. It seems to be possible, however, to compensate for this by making the distribution of the windings not quite uniform. The final distribution may be calculated as soon as the final pole profile will be known.

For the "geometrical error" at the closed side of the gap (i.e. the decrease of n for increasing r) a separate winding section might be used. The power required would probably not be very large.

2. Excitation in series or parallel; thickness of wires.

For achieving a smooth relationship between the gradient correction and r , especially at some distance of the median plane, it is desirable to have the wire dimensions as small as possible. Obviously, with many thin wires the desired current distribution may be approximated in a better way than with a few thick ones. The eddy current considerations point in the same direction.

If all the windings are connected in series, however, a high exciting voltage would be required for thin wires. For example, for the saturation compensation according to the scheme of fig. 2, a peak voltage of 1500 V would be necessary if all the focusing half units (i.e. half of the machine) would be connected in series, using bars of $2 \times 7\ mm^2$ cross section. (This may be calculated from (3), appendix 2).

A way of solving this problem would be to use several generators, distributed equally over the circuit, as illustrated in fig. 4. In this way, the voltage with respect to earth might be kept low; on the other hand, the use of several generators instead of one would make the method more expensive and less reliable.

We shall see, however, that, if some care is taken, it will be possible to connect separate parts of the windings in parallel. To make this clear, we have to consider the consequences of parallel connections in some detail. We may divide these considerations into 2 parts:

a. Connecting different units (or groups of units) in parallel,

b. parallel connection of different parts of windings on the same unit(s).

a. The voltage induced in a poleface winding by the changing main flux may be compensated as well as possible by dividing the return connections between the two sides in the right way. Even then, a perfect compensation can never be obtained, as we have to use a whole number of return windings. (Also, the different changes in μ in different parts of the profile, will prevent a perfect compensation to be achieved throughout the whole cycle. The latter effect is, however, less important, as the influence of induced voltages is only felt in the beginning of the cycle).

If the number of returns on both sides is chosen in the best possible way, the maximum induced voltage may be equal to half the voltage in one magnet exciting turn, multiplied by two (for 2 polefaces), i.e. 2,5 V/unit.

If the induced voltage would be the same for every unit, we might easily connect the different units (or groups of units) in parallel. However, the magnitude of this voltage will depend strongly upon the exact radial position of the poleface windings. We shall calculate the magnitude of this effect for the nearly-uniform current distribution required for the compensation of saturation.

A radial displacement δ of the whole "current sheet" on one of the two pole faces of one unit would, if conductors of width δ were used, have the same effect as displacing one winding from $r = +10$ to $r = -10$. As 50 o/o of the total flux passes between these two points, an induced voltage of $0{,}5 \times 1{,}25\ V \approx 0{,}6\ V$ would be the result. For windings with a width d this voltage would be $\frac{0{,}6\ \delta}{d}$ V. We suppose now, that the maximum exciting voltage (at 14 Kgauss) is as high as practicable; in this case more units may be connected in series, and the difficulties are minimised. This maximum voltage will have the order of magnitude of 1000 V.

If m units are connected in a series "group", we may reasonably expect a total induced voltage

$$V_{ind} = 0{,}6 \frac{\delta}{d} \sqrt{2m} \quad \text{volt},$$

if δ is the standard deviation of the displacement (the factor 2, because every unit has 2 polefaces). From this expression d may be eliminated by means of equation (3), appendix 2. We find that the total induced voltage in m units may be equal to

$$V_{ind} = \frac{0,6\ a\ V_{unit}\ \delta \sqrt{2m}}{3\ J\ D\ L\ \rho}\ \text{volt.}$$

As we supposed $mV_{unit} = 1000$ V, we find, substituting the figures mentioned in appendix 2, and $\delta = 0,5$ mm:

$$V_{ind} \approx \frac{2}{\sqrt{m}}\ \text{volt.}$$

At 14 Kgauss a 7,5 o/o n-variation is produced on the equilibrium orbit by an exciting voltage of 1000 V. At injection the influence of the same voltage is 100 x as large. This means that the difference of induced voltage in two parallel winding groups will cause a n-difference between the two groups

$$\frac{\Delta n}{n} = \frac{2 \cdot 100 \cdot 7,5}{\sqrt{2m} \cdot 1000}\ \text{o/o} = \frac{1,5}{\sqrt{2m}}\ \text{o/o} .$$

For focusing and defocusing magnets separate exciting systems have to be used. This means that the greatest value of m of practical interest would be 25, giving a possible difference between thegroups of 0,21 o/o at the equilibrium orbit,and somewhat more at the narrow part of the gap. Of course, this is a "standard deviation", and the real error might be larger. It seems, however, to be tolerable. As the error is opposite in both groups, the situation might be improved by spacing the units belonging to every group equally over the ring circumference.

Even a smaller m value might be possible (although there will probably be other causes for unequal induced voltages), if we adopt some scheme for equalizing the voltages, for instance with a current transformer in the main excitation circuit.

In this way the width of the bars could be made smaller, and the corrections more smoothly dependent on r . However, too many wires would make the interconnections to the return windings at the end of every half unit very complicated.

b. Another method of obtaining a smooth current distribution would be to connect different bars (or series groups of bars) on the same unit (or group of units) in parallel with different series resistors. In this case much more freedom would exist for choosing (and changing) the current distribution. However, the "induced voltage" problem might become a serious one for the following reasons:

1. Even in the absence of radial misalignment of the windings, the induced voltage due to the necessity of using a whole number of return windings will not necessarily be equal for the parallel groups.

2. This induced voltage will be relatively large compared with the exciting voltage, as only a small part of the total number of bars is considered.

3. As the induced voltage is the same for all units, its influence cannot be made smaller (as in case a, where a random voltage occurred) by connecting more units in series.

4. The influence of the current caused by this voltage cannot be cancelled, as in case a, by grouping the units in a special way around the ring circumference. It will produce an uncotrollable irregularity in the n-r-plateau, especially near injection.

In view of the four points considered above it would probably be impossible to obtain the right current distribution by means of parallel connection of different bars (with different resistances) on the same unit. Only if series resistors, high compared to the winding resistance, would be used, it might be possible; the power consumption would in this case limit the application of the method to low fields.

As an illustration of case b a rough example will be given. We shall suppose that it would be desirable to make a n-versus-r-correction throughout the whole cycle as indicated in fig. 5 (solid line) by connecting in parallel two sets of bars (No. 1 and 2), each giving a correction per unit of current as indicated by dashed lines 1 and 2. For obtaining the desired correction, it would be necessary to attenuate the current through No. 2 two times. This means that the No. 2 bar(s) would have twice the resistance of the No. 1 bar(s).

If we suppose for the moment that the difference of induced voltage between the two sets of bars would be $\frac{1}{500}$ of the peak energizing voltage (at 14 Kgauss), the circulating current caused by this voltage difference would be $\frac{1}{1500}$ of the peak current in section 1, and $\frac{1}{750}$ of the same in section 2. At injection the influence of this current would be 100 times as high as at 14 Kgauss. Therefore the obtained n-correction would be 7 o/o too high for section one and 13 o/o too low for section 2 (or the opposite). This might just be tolerable. However, it is very difficult to satisfy the condition that the induced voltage is 500 times as small as the peak energizing voltage, because the first will be between 0 and 2,5 V/unit, whereas a peak exciting voltage of 10 V/unit would already mean a very small wire diameter, resulting in a low space economy and complicated return connections. It seems that thte disturbing effect may be two orders of magnitude too large.

The series connection of wires, each of them parelleled by resistors, would result in the same difficulties, as may be shown in a similar way.

The consequence of these difficulties is, that we may change the current distribution only by changing the position of individual bars or (after the bars have been fixed) by using only part of them. All bars on the same unit have to be connected in series, except if separate energizing means are provided. In this case, a current feedback applied across the current source (necessary in any case for achieving the required accuracy) will reduce the errors caused by induced voltages.

In any case it will be necessary to a certain extent to fix the aims which have to be served by the poleface windings before they can be designed.

3. Corrections at start of cycle with the same windings.

The windings, necessary for compensating saturation effects, will occupy most of the available space, especially between $r = 0$ and $r = 5$ (closed side). If a separate winding for corrections at low fields would be required, it seems very likely that 40 o/o more space would be occupied; even for low current windings, the insulation thickness would occupy this extra space. In any case it would be very satisfactory if the same windings could be used for compensations at both high and low fields.

This would mean that the current at low fields would have to be controlled very accurately. In fact, if the peak current causes a n change of 7 o/o at the equilibrium orbit at 14Kgauss (as will be necessary), and if we want to keep random n-fluctuations at injection down to 0,1 o/o, the maximum tolerable current error at injection will be $\frac{1}{7000}$ of the peak current. As will be shown, this precision may be reached, even with a programmed system of excitation.

If we would connect the windings to a generator or an amplidyne, and reduce the field excitation of this machine to zero, the output current would not be zero, due to the voltage induced in the windings by the main field, and (much more) to the hysteresis of the generator field. The latter is especially bad in the case of an amplidyne, where the output value at deenergized field may be as much as 70 o/o of the peak value.

These effects may be reduced greatly by applying a high degree of current feedback around the machine, as indicated in fig. 6. It may be shown, however, that the simple arrangement of fig. 6 would not be satisfactory, as the "time lags" in the feedback loop would cause oscillations at a relatively low loop gain. The amplidyne produces two time lags, due to the selfinductance of the control field and the cross field respectively; the order of magnitude of these time constants is for most machines 0,2 sec and 0,1 sec. Another time constant is introduced by the reactivity of the poleface windings and the generator armature. For the first experimental windings 0,005 sec was measured (see report MM19); the increase of the copper cross section compared to the insulation will cause an increase of this value, probably to about 0,01 sec.

A great improvement could be achieved by using two separate feedback loops, one providing voltage feedback, and the other current feedback (fig. 7). In this way, the time constant of the windings would not cause difficulties. By means of filters, as indicated, stability could be obtained. For an output precision of 1 : 7000, and a hysteresis value of 70 o/o, it is found to be sufficient to have a loopgain of 70 times for both feedback loops, which does not seem to be too difficult. This system would reduce the hysteresis effect 5000 times, but the "induced voltage" effect only 70 times, as the voltage feedback does not help to reduce this. This would, however, be quite good enough.

The feedback system stability will not be considered here in detail; a calculation has shown that it will not present great difficulties.

Another condition that must be fulfilled for using the same windings for high and low fields, is that the current distribution in each section of the windings has the right shape for both corrections. As may be concluded from MM17, fig. 5, this will be roughly the case. Anyway, the n-deviation at injection will have the order of magnitude of 1 o/o ; a high degree of precision in the correction does not seem to be necessary.

4. Conclusions.

1. The poleface windings may correct n-deviations in the narrow part of the gap much more easily than in the wide part.

2. Shifting the n value more than 2 o/o in the wide part of the gap during the whole cycle cannot easily be done with the poleface windings.

3. Different groups of units may be energized in parallel, if the units of every group are distributed equally about the ring circumference. Special measures may benecessary if the groups are small.

4. It will be extremely difficult, and probably impossible, to choose the desired current distribution as a function of r by way of parallel connection of poleface bars at different values of r, using different series resistors.

5. This means that changing the current distribution after installation of the windings may only be done by not using some of the bars, except if separate exciting systems for the different sections are used.

6. The same windings and exciting system may be used for high and low field corrections.

Appendix 1.

The eddy current distribution in a poleface bar with thin rectangular cross section (dimensions as indicated in fig. 8) may be described by the equation

$$di = \frac{ax}{\rho} \frac{dB}{dt} dx ,$$

ρ being the specific resistance of the material.

The influence of these currents upon the field in the median plane may be roughly approximated by supposing the polefaces to be parallel, as illustrated in fig. 8. We take into account the first mirror images only. (This is justified because we shall find Δn to decrease rapidly as p increases).

We find for the vertical field component in the point P

$$B = 8 \cdot 10^{-7} \int_{-d/2}^{+d/2} \frac{ax}{\rho} \cdot \frac{dB}{dt} \cdot \frac{q - x}{(q - x)^2 + p^2} dx$$

$$= 8 \cdot 10^{-7} \frac{a}{\rho} \frac{dB}{dt} \left(-d + \frac{q}{2} \ln \frac{(q + \frac{d}{2})^2 + p^2}{(q - \frac{d}{2})^2 + p^2} + p \operatorname{arctg} \frac{p\,d}{p^2 + q^2 - (\frac{d}{2})^2} \right)$$

(B in Wb/m^2, ρ in Ωm, t in sec, all distances in m).

For the gradient we find (supposing $\frac{d}{2} < p$):

$$\frac{dB}{dq} = \frac{4 \cdot 10^{-7} q\, a\, d^3}{\rho} \cdot \frac{dB}{dt} \cdot \frac{p^2 - 3q^2}{(p^2 + q^2)^3} ,$$

giving for the n-error:

$$n = \frac{4 \cdot 10^{-7} q\, a\, d^3 R_o}{\rho B_o} \cdot \frac{dB}{dt} \cdot \frac{p^2 - 3q^2}{(p^2 + q^2)^3} .$$

The effect at injection for a bar of 7 x 2 mm^2 at $r = 7$ (open side) is shown in fig. 9.

Fig. 10 shows the same for 5 such bars between $r = - 10$ and $r = - 6$ (closed side).

If the whole poleface is covered with a "sheet" of equal bars at equal distances, the effects of single bars tend to cancel out in the median plane. In fact, earlier measurements showed that a set of 1,5 x 10 mm^2 bars, divided equally and with short distances over 16 cm of the poleface width only produced a 0,7 o/o n change at $r = 6$, whereas bars of 1,5 x 5 mm^2 did not show any measurable disturbance.

Appendix 2.

From fig. 2, and the model measurements, the peak current density J, required for compensation of the saturation effects, may be found. If the width and thickness of the bars is d , resp. a , we find for the peak current:

$$I = J\, d \,, \tag{1}$$

and for the resistance per unit (length L)

$$R = 2 \cdot 1{,}5 \cdot \frac{D}{d} \cdot \frac{L\rho}{ad} \,. \tag{2}$$

(ρ = spec. resistance,
D = total width of current sheet).

The factor 2 is used, because there are 2 polefaces; the factor 1,5 is caused by the return windings resistance, which is supposed to be half that of the actual windings.

The peak voltage per unit is

$$V_{unit} = \frac{3\, J\, D\, L\, \rho}{a\, d} \tag{3}$$

The peak power for the whole machine is

$$100 \quad I^2 R = 300\, J^2 \frac{D\, L\, \rho}{a} \tag{4}$$

By substituting

J = 90 A/cm for 14 Kgauss, or
26 A/cm for 12 Kgauss;

D = 20 cm;

L = 470 cm;

$\rho = 17 \cdot 10^{-7}\, \Omega\,$cm;

a = 0,2 cm,

we find a peak power of 200 KW for 14 Kgauss, or 17 KW for 12 Kgauss.

The required gradient correction as a function of time at the equilibrium orbit is shown in fig. 11. This curve was derived from measurements on model No. 8. It is supposed that the supply voltage for the main coils is being kept constant throughout the cycle. The curve is nearly the same for different r-values, and may be described with a good accuracy by the equation

$$\frac{G_t}{G_{14\ kg}} = 6{,}2\ (t - 0{,}79)^2 \qquad (t \text{ in sec, } t > 0{,}79)$$

By using this approximation, the average power may be found from the peak power at 14 Kgauss by multiplying with a factor

$$\frac{1}{5} \int_{0{,}79}^{1{,}19} 6{,}2^2\ (t - 0{,}79)^4\ dt = 0{,}016$$

for operation up to 14 Kgauss (cycle of 5 seconds), or

$$\frac{1}{3} \int_{0{,}79}^{1} 6{,}2^2\ (t - 0{,}79)^4\ dt = 0{,}001$$

for operation up to 12 Kgauss (cycle of 3 seconds).

The required average power for the considered correction would be 3,2 KW, or 0,2 KW, respectively.

If we suppose the insulation between the bars to occupy 10 o/o of the available space, the current will have to increase with 10 o/o, and as the resistance will also increase with 10 o/o, all powers will have to be multiplied by 1,3, giving the following result:

B_{max} (gauss)	Power (KW)	
	Peak	Average
12000	22	0,26
14000	260	4,2

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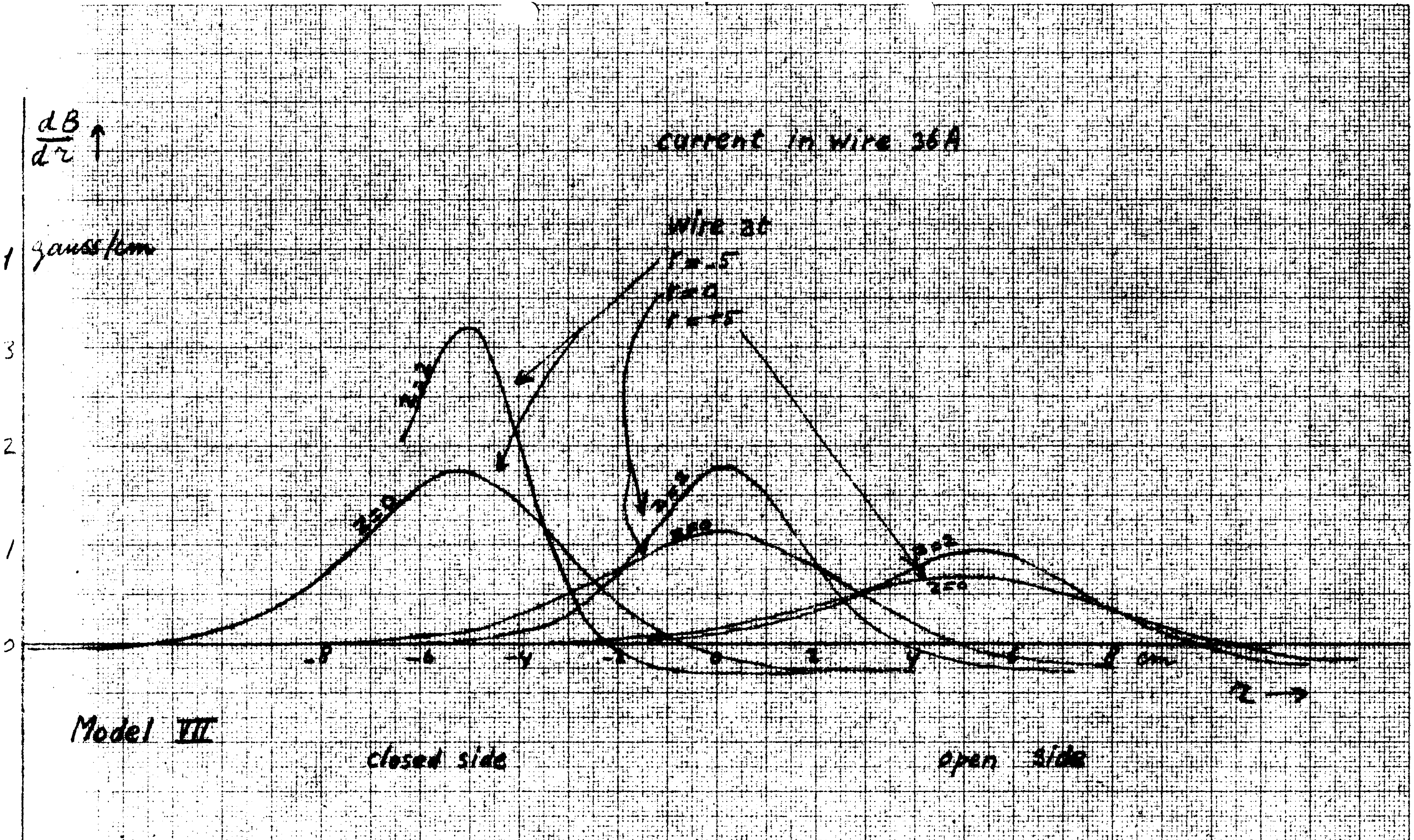
March 1956



dB/dr
gauss/cm
current in wire 36A
wire at
r=-5
r=0
r=+5
z=2
z=0
-8
-6
-4
-2
0
2
4
6
8 cm
r
Model VII
closed side
open side
0
1
2
3

Fig. 1

Model VII

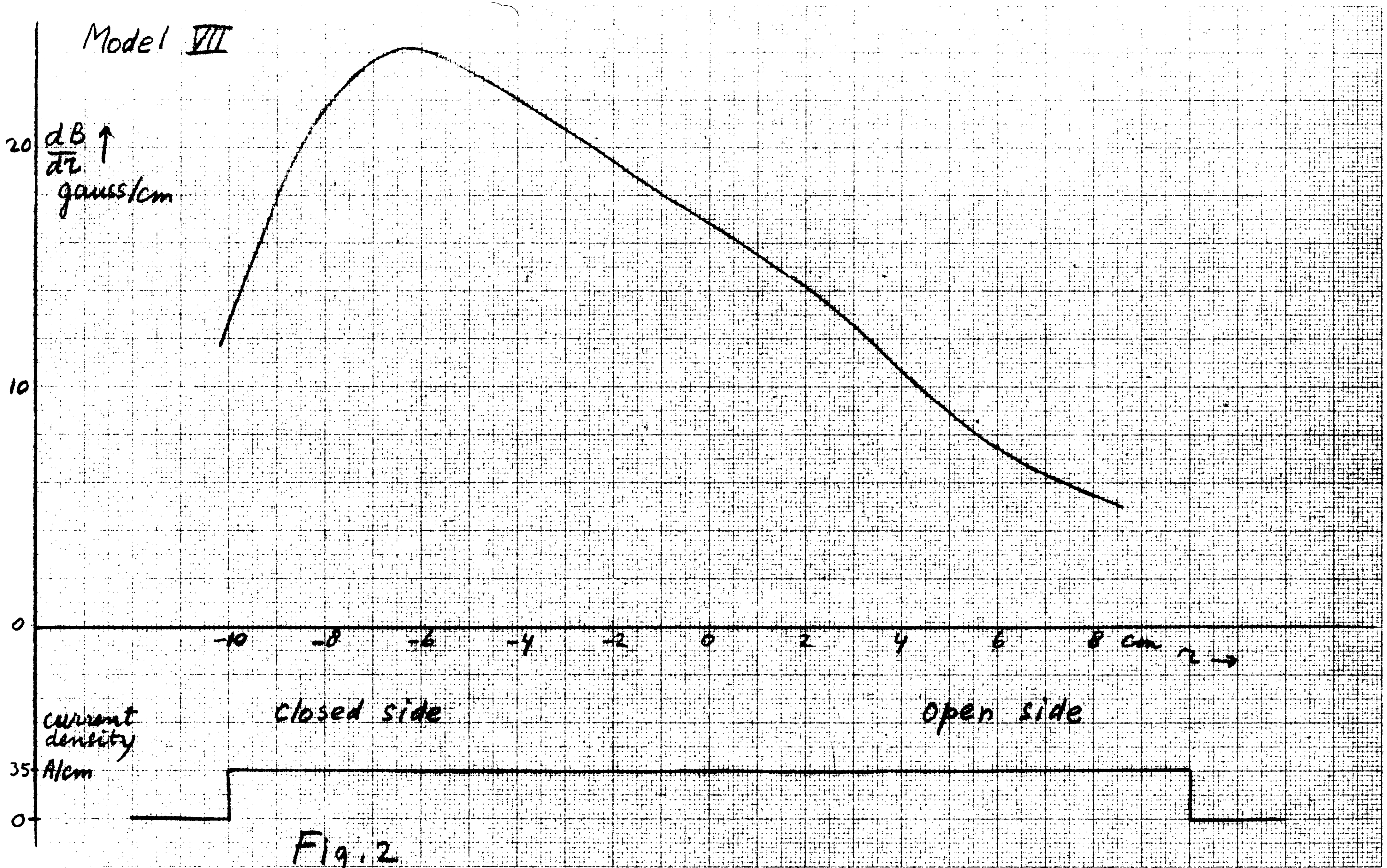
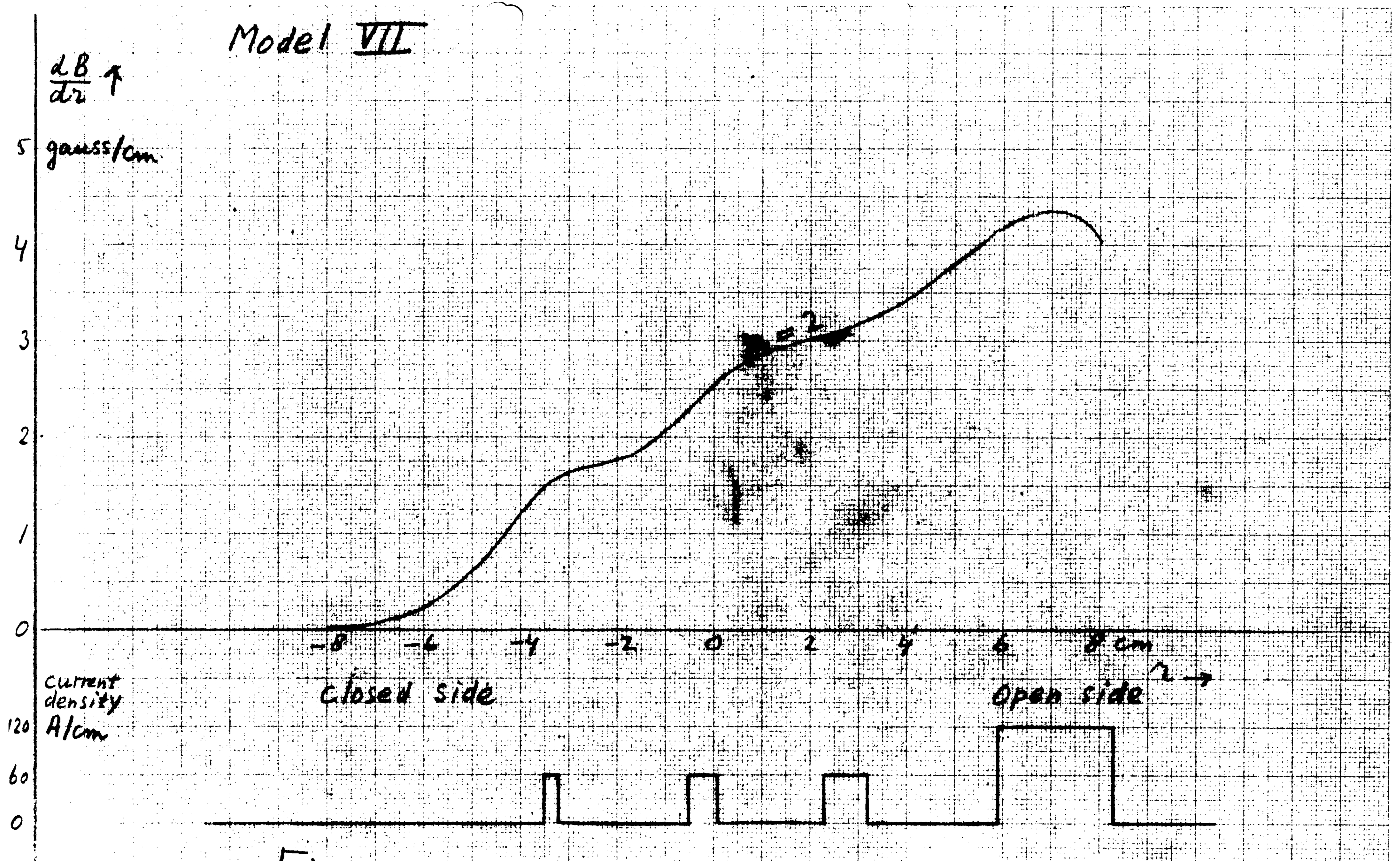


Fig. 2



Model VII
dB/dr ↑
gauss/cm
5
4
3
2
1
0
-8
-6
-4
-2
0
2
4
6
8 cm
r →
closed side
open side
current density
A/cm
120
60
0

Fig. 3

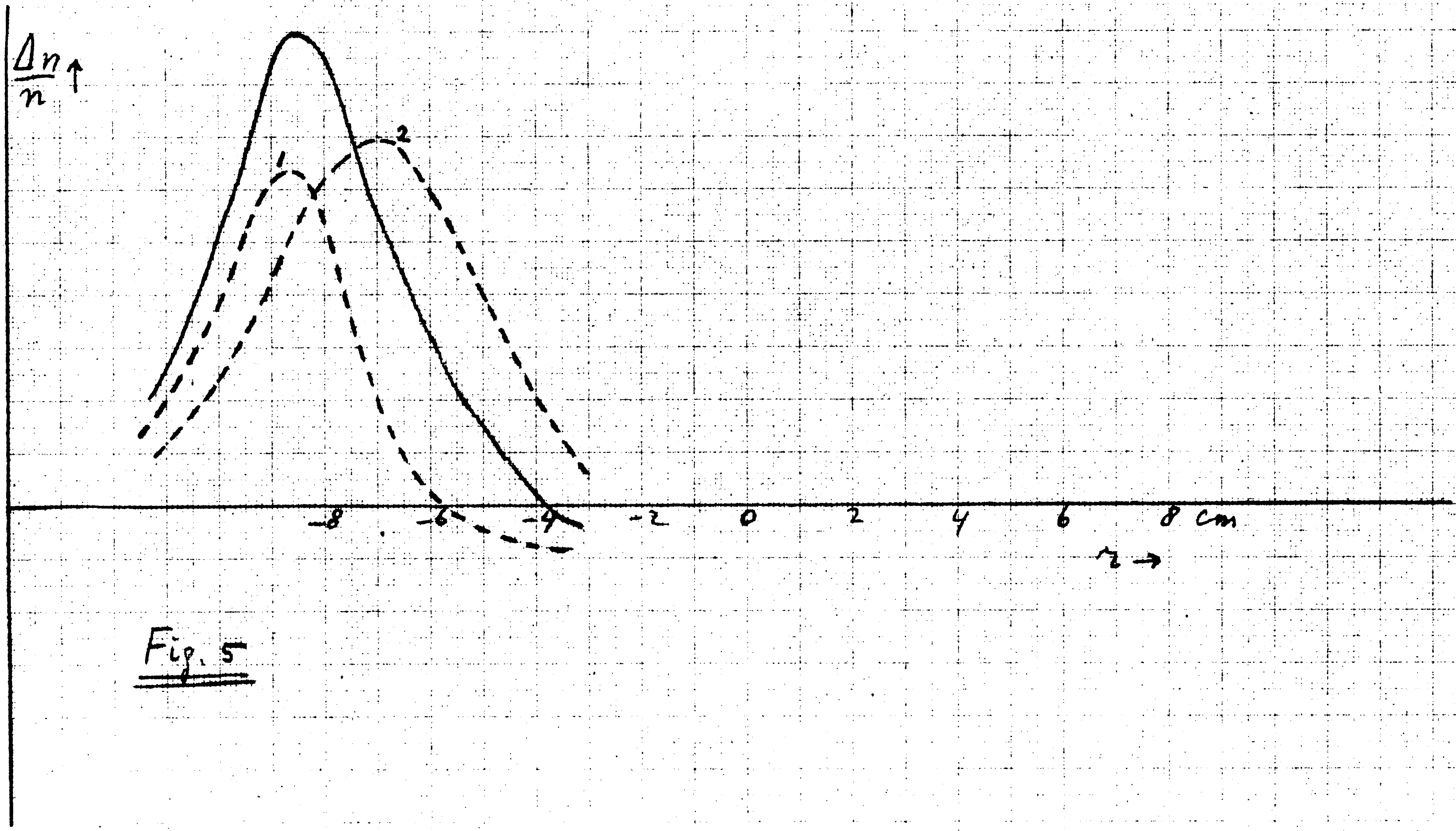


Fig. 5

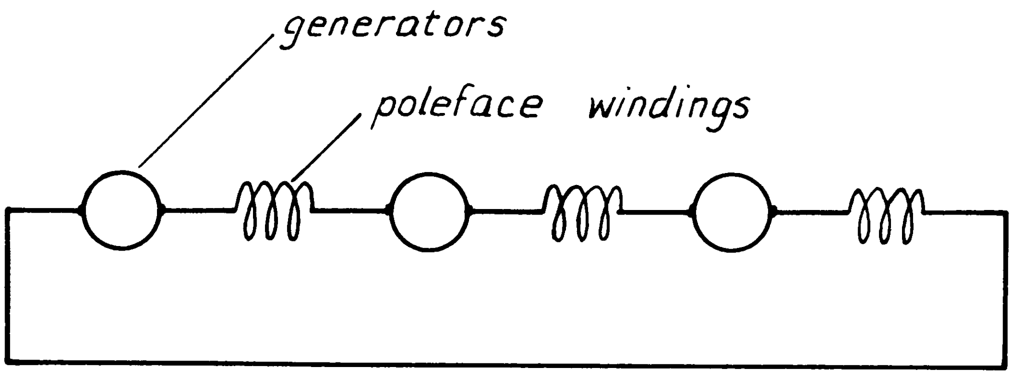


fig. 4

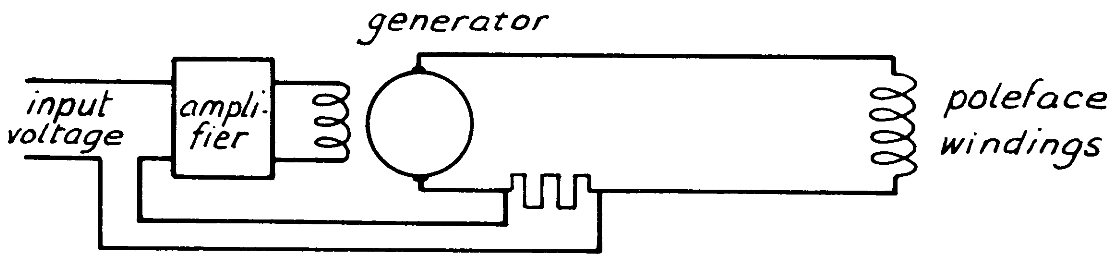


fig. 6

Item Pos.	No. req. Nb. de p.	Descriptions	Material Matière	Pattern Modèle	Observations
1 11					
2 12					
3 13	III II I			Scale Echelle	CERN - GENÈVE
4 14					
5 15					
6 16					
7 17		Modifications	Signatures		
8 18					
9 19					
10 20					

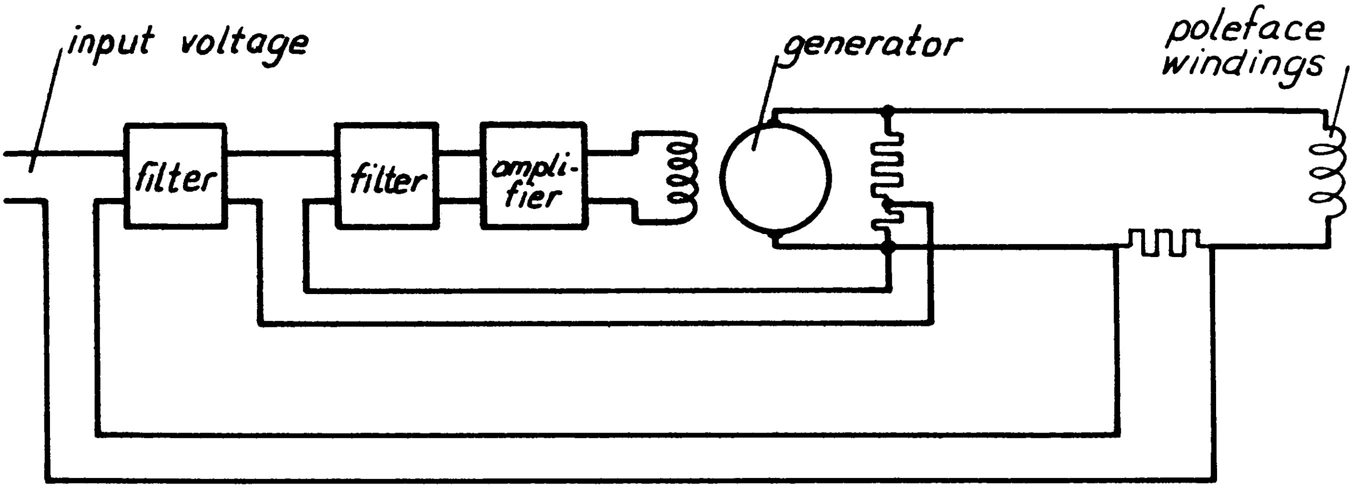

input voltage
filter
filter
ampli-
fier
generator
poleface
windings

fig. 7

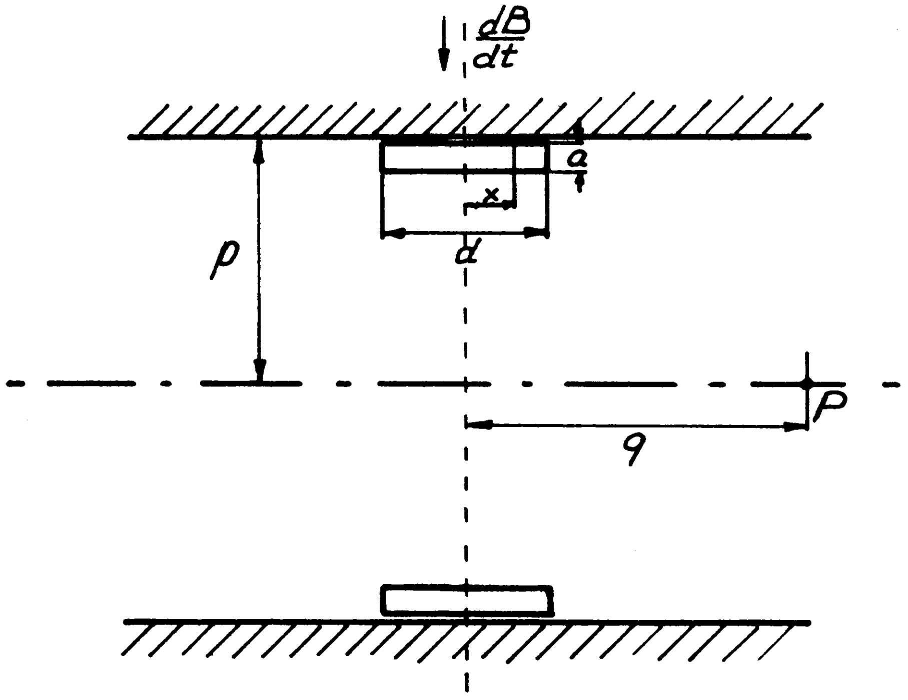

dB
dt
a
x
d
p
P
q

fig. 8

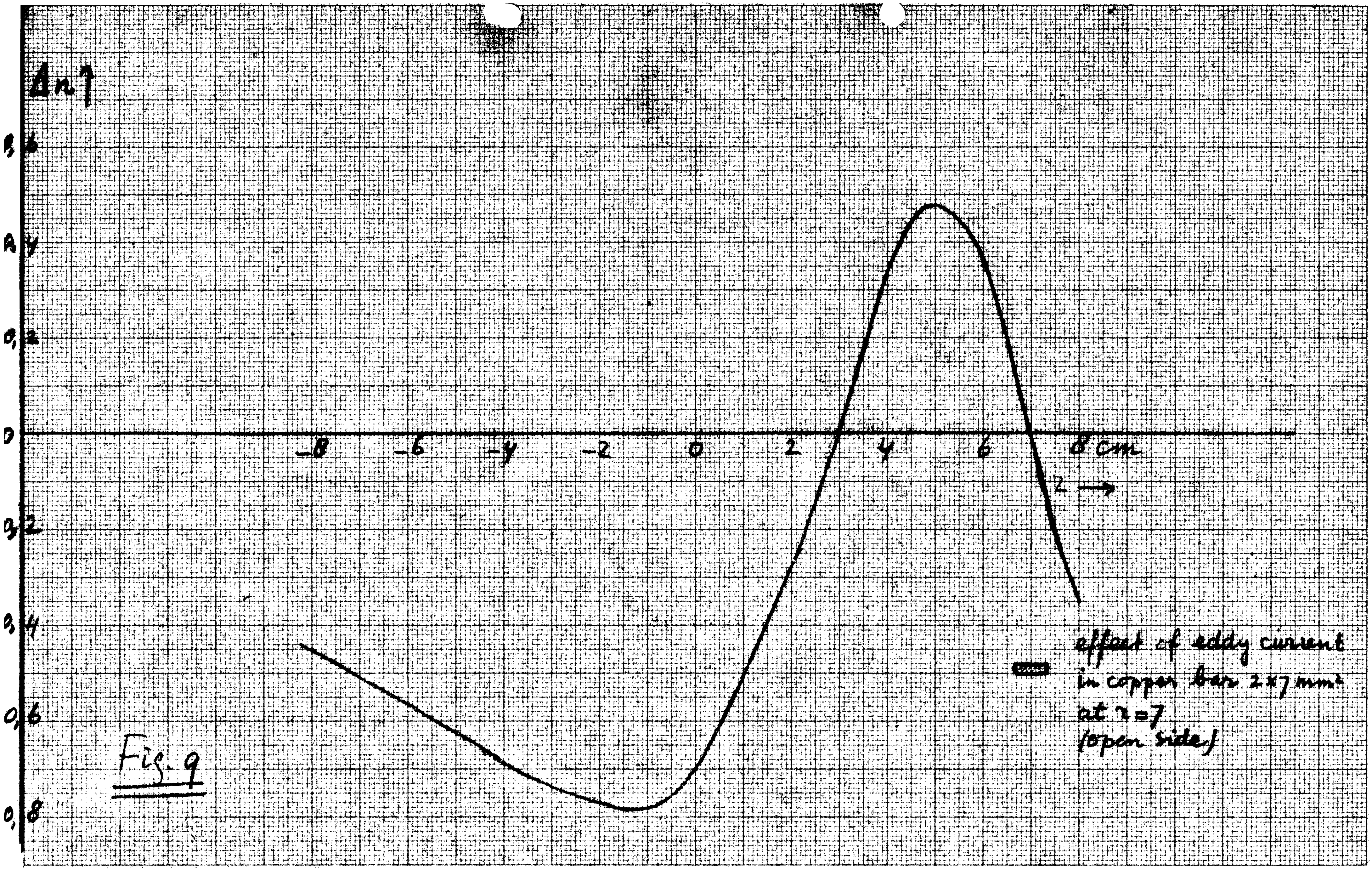

Δn
0,6
0,4
0,2
0
0,2
0,4
0,6
0,8
-8
-6
-4
-2
0
2
4
6
8 cm
z
effect of eddy current
in copper bar 2×7 mm²
at r=7
(open side)

Fig. 9

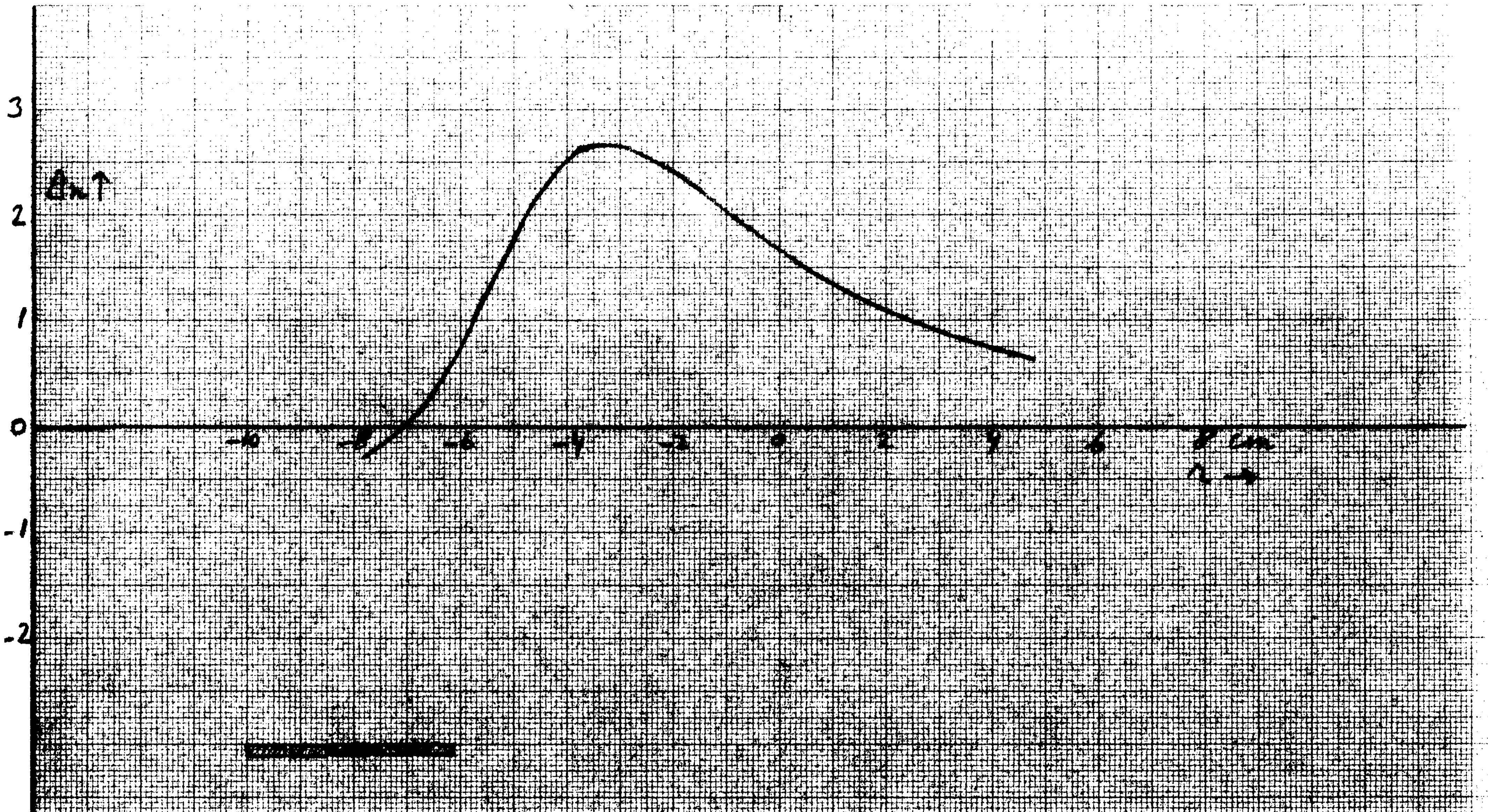
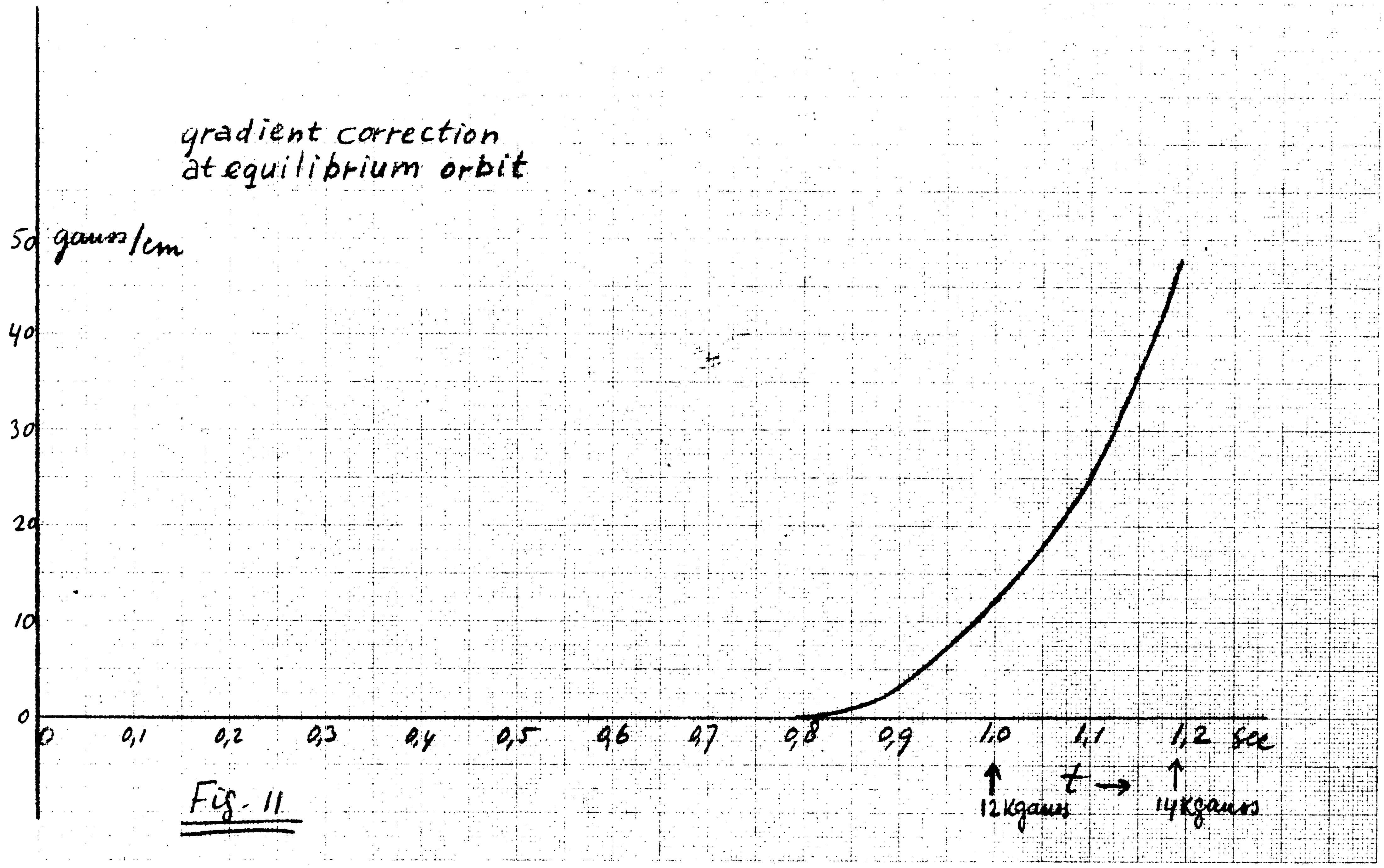


Fig. 10



gradient correction
at equilibrium orbit
gauss/cm
50
40
30
20
10
0
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
sec
t
12 Kgauss
14 Kgauss

Fig. 11