A single turn coil for fast electron ring compression and magnetic expansion acceleration

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IPP 0/10 March 1972

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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Abstract

A single turn coil for fast electron ring compression to reduce broadening of smaller ring dimensions due to resonances and to provide a convenient shape for magnetic ring expansion acceleration is described, and numerical calculations are presented.

A. Introduction

In present electron ring experiments for collective ion acceleration some of the major problems occur at the beginning and at the end of the compression cycle. Resonances (besides collective instabilities) and magnetic field inhomogeneities mainly at the beginning and the $\nu_r = 1$ resonance and the B_r-behaviour at the end of the compression and roll-out phase tend to limit the holding power or effective acceleration rate. The limitation due to resonances can be overcome by the choice of a suitable magnetic field shape or by high compression velocity, while for the right B_r-dependence at the roll-out and acceleration stage (especially at small numbers of the holding power) a smooth current distribution in the magnetic field coils is necessary.

Therefore one may think of a long single turn compression- and acceleration coil (combined with a small one), which gives a very fast initial compression because of the low inductance of this coil, and which leads to a smooth behaviour of the magnetic field components in the acceleration part, as its current distribution is continuous. Even if the application of such a coil with relatively large volume is unfavourable with regards to energy saving, it might(because of its simplicity)probably serve as a first model to study the initial stages of collective ion acceleration at still small rate.

B. The Arrangement

The contour of the compression and magnetic expansion coil can roughly be seen from Fig. 1, where the coordinates of the current filaments used for the numerical calculation[1] are plotted in R and z. The coil is more or less cylindrical with a length of 75 cm and a mean diameter of 32 cm. At one side it has a bump, which provides a field index $n = -\frac{R}{B_z}\cdot\frac{\partial B_z}{\partial R}$ of about 0.55 around the injection radius of 16 cm, so that (with $\nu_r \approx \frac{2}{3}$) multiturn inflection is easily possible (Lambertson method).

From Fig. 2 one may find, that n is dropping down monotonically to very small values at smaller radii. This radial dependence of n is similar to that of the first coil pair in the present Garching compression arrangement[2], where experiments didn't show drastic particle losses, but axial broadening due to the Walkinshaw resonance at n = 0.2.

As the new coil has an inductance of only L_c = 105.6 nH, the initial compression with this coil is by one order of magnitude faster than with the old arrangement, so that the G-factor[3] for the most dangerous resonance, the Walkinshaw resonance, is less than about 0.2, which shouldn't lead to strong axial broadening. With this fast radial compression (initially approximately 2 mm per electron revolution) the other resonances are also crossed very fast, and the electron ring gets free from the snout with its magnetic field disturbance in a very short time. The time dependence of radius R and magnetic field index n for the initial phase is plotted in Fig. 3.

At current maximum, which is reached at T = 9.4 μsec, the field index has gone down to n = 0.002 at a radius of R=2.3 cm

and a magnetic field strength of B_z = 19.6 kG. When the coil is crowbarred at this time, a small coil, situated at R≈6 cm and z ≈-6 cm (see Fig. 1) can be switched at any instant during a relatively long time interval.

This coil provides the roll-out and spill-out of the electron ring into the acceleration section, which is made to have a smooth B_r-dependence. The B_r-behaviour during the roll-out phase is drawn in a rough scale in Fig. 4, while Figs. 5a) and b) give the radial magnetic field component B_r more sensitively at the spill-out point. In both last Figures the main coil is crowbarred at 9.4 μs. In Fig. 5a) the small coil ("blow coil") is switched at 9.4 μs, while in Fig. 5b) it is triggered as late as at 20 μs. Both B_r-distributions look quite similar, so that there is some time for ionization and ion loading of the electron ring.

The B_r-field for acceleration is chosen to be about 5 G, which corresponds to the present (February 1972), still relatively small holding powers, that have been reached with an electron number of $N_e = 5 \cdot 10^{12}$ and a minor radius of smaller than about .5 cm at R = 2.5 cm.

The B_r-dependence on z is smooth, because the current distribution in the main coil is continuous and the current carrying layers are far away from the ring. Because of this reason the derivatives of B_r, which tend to impose lower bounds on ring self-focussing[4], are very small, as desired: at spill-out we have for the field components $\frac{\partial B_r}{\partial r} < 0.5 \frac{G}{cm}$, $\frac{\partial^2 B_r}{\partial z^2} < 1 \frac{G}{cm^2}$,

and in the post-spill phase there is

$\frac{\partial B_r}{\partial r} < 4 \frac{G}{cm}$ and $\frac{\partial B_r}{\partial z} < 1 \frac{G}{cm}$, which seems to be quite sufficient.

The mean value of B_r can easily be changed by a stationary field from small coils sitting on an iron core in a conducting tube[5] coaxial to the main magnetic field axis, whose penetration is prevented. Thus, according to the holding power, acceleration field strengths of, say $B_r \approx 2$ G up to $B_r \approx 20$ G may be achieved.

The conducting tube (with a radius smaller than the electron ring radius in compressed state) might also serve as a center conductor for the axial current providing a B_ϕ -field. An application of this ancillary azimuthal magnetic field seems to be important for shifting betatron tunes[6] to avoid resonances, especially the most dangerous $\nu = 1$ - resonance, and to increase Landau-damping coefficients for transverse collective instabilities[7]. In the case of the single-turn main compression coil the application of an axial current to get suitable tunes and damping coefficients is very easy and can be done by a single stage LC-circuit. The electrical parameters for this axial current device are given together with the data for the main compression coil and the small "blow-coil" in Table I.

Table I

	Main coil	"blow coil"	B_ϕ -device
Voltage (kV)	30.0	30.0	30.0
Capacity (μF)	330.0	15.0	20.0
Circuit inductance (μH)	0.116	0.389	2.45
Mutual inductance (μH)	0.0145	0.0145	-
Circuit resistance (mΩ)	0.52	2.0	20.0
Crowbar inductance (μH)	0.007	0.2	0.2
Crowbar resistance (mΩ)	0.5	2.0	10.0
Switching time (μsec)	0.0	≥ 9.4	-1.9

With the electrical parameters (using B_ϕ) one gets a smooth behaviour of the tunes, as curve b) in Fig. 6 indicates, and thus gets free from the dangerous $\nu = 1$ - resonance. Curve a) gives the case without B_ϕ. Applying the azimuthal field B_ϕ the remaining resonances, $\nu_A + 2\nu_B = 2$ and $3\nu_B = 1$ are crossed with very high speed, as Fig. 7 demonstrates, thus being harmless. The Landau-damping coefficients[7] for transverse collective instabilities are all very high in amount (above 1000 μs^{-1}).

The use of additional focussing by image forces[8] at the presence of azimuthal fields hasn't been solved theoretically yet.

The single-coil system, which seems to have some advantages from experimental view (only 2 switching times; the coil can be used as the vacuum-chamber[9]; the return-conductor for the axial current serves as symmetrising flux-barrier for the axial field component), may probably show strong collective or cavity radiation[10]. But this radiation might be damped by resistive structures or might be suppressed by nearby elements as the "squirrel cage" and the axial rod.

The disadvantage of the inflexibility of the n-pattern of this coil can be overcome by variation of the tunes with B_ϕ in a relatively wide range. Moreover conducting elements can be put into the interior of the coil which change the n-dependence on R; one may profit from the time dependence due to bad conducting, mechanically strong structures (as stainless steel).

C. Acknowledgements

The author is grateful to E. Springmann, who skilfully carried out the calculations. We both want to thank Dr. A.U. Luccio for the use of his program[1], developed for electron ring compression, roll-out and spill-out. Numerous discussions with my colleagues of the RP-group are gratefully acknowledged.

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Figure captions

Fig. 1 R, z-contour of the coil.

Fig. 2 Magnetic field index n as a function of radius R.

Fig. 3 Time dependence of radius R and magnetic field index n.

Fig. 4 Plot of B_r during the roll-out phase.

Fig. 5 B_r-dependence on z for different switching time of the "blow coil" (a and b).

Fig. 6 Betatron tunes without (a) and with (b) azimuthal magnetic field B_ϕ.

Fig. 7 Time behaviour of the tunes.

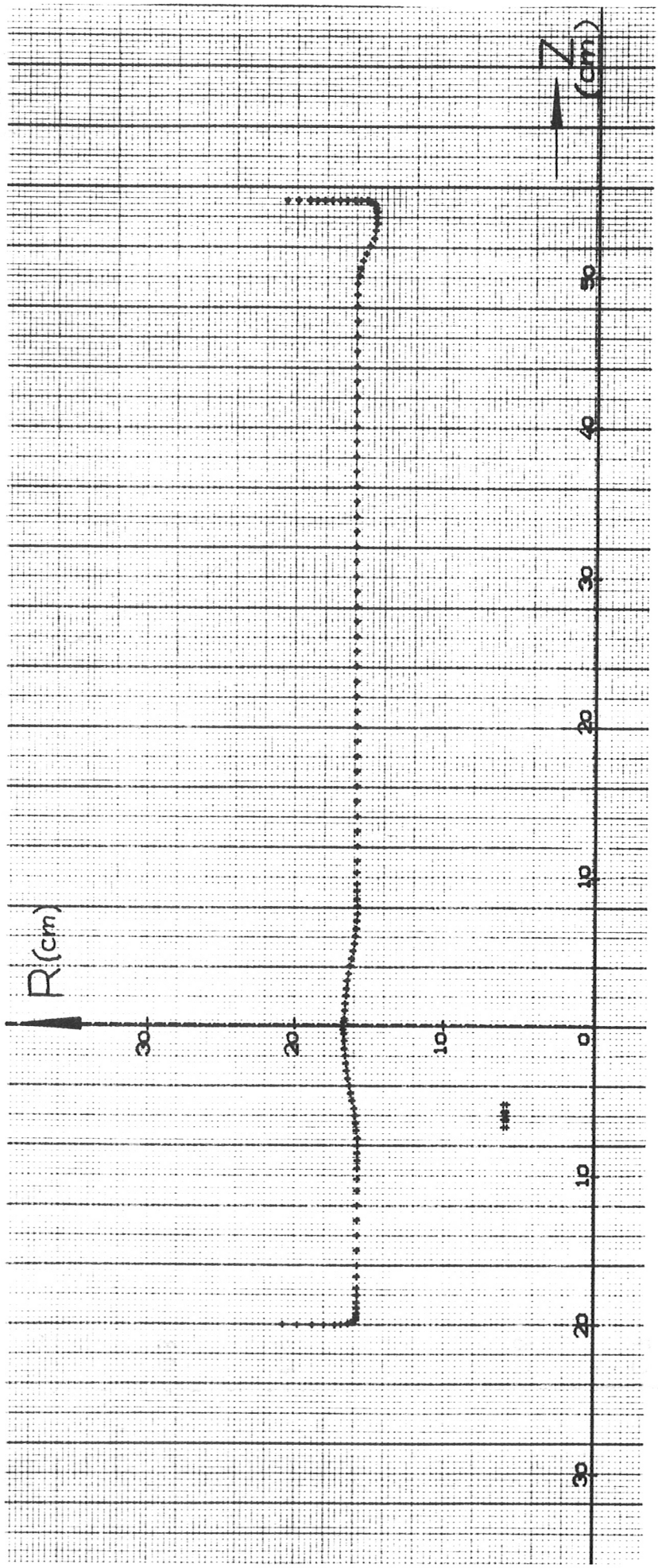

Fig.1

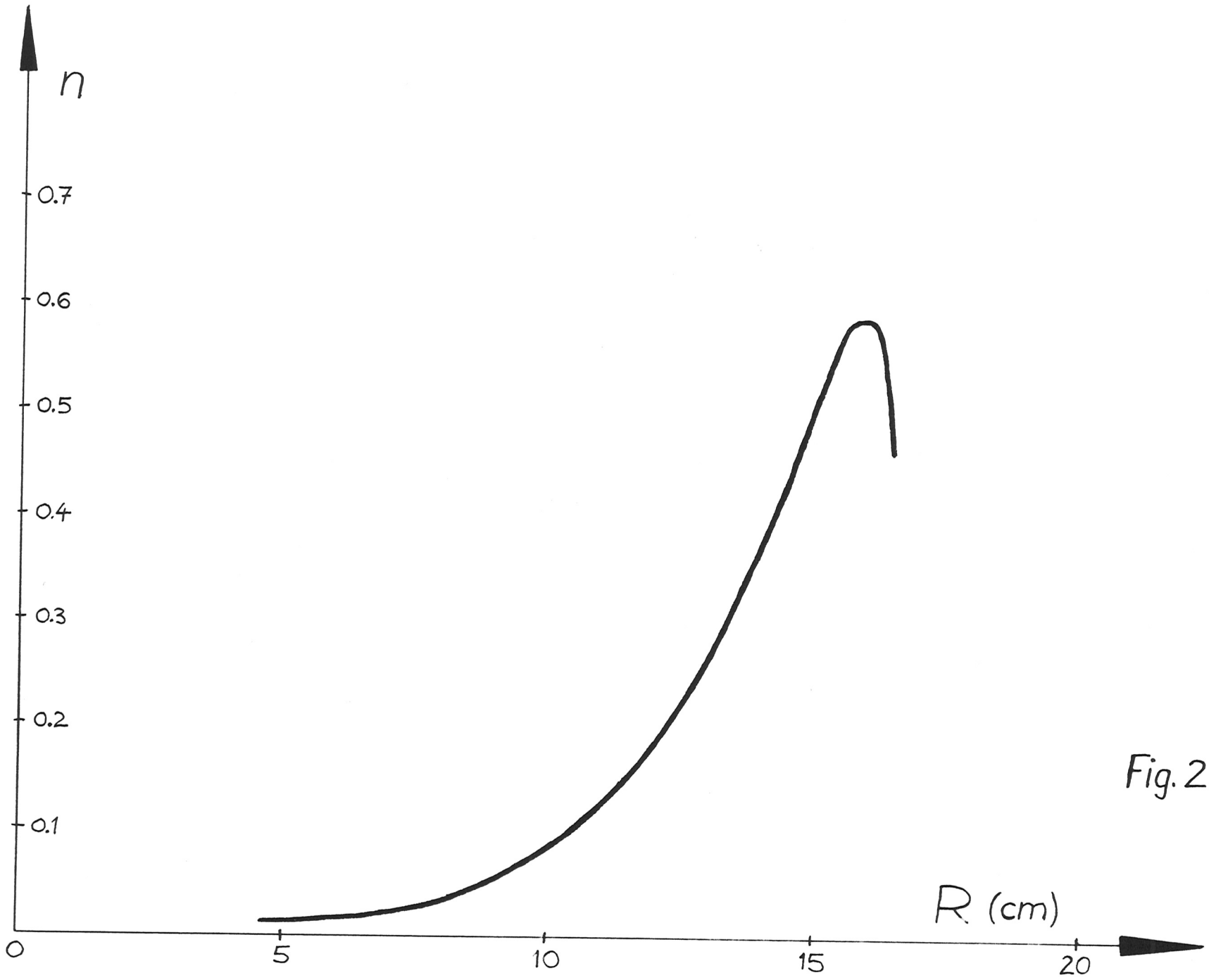

Fig. 2

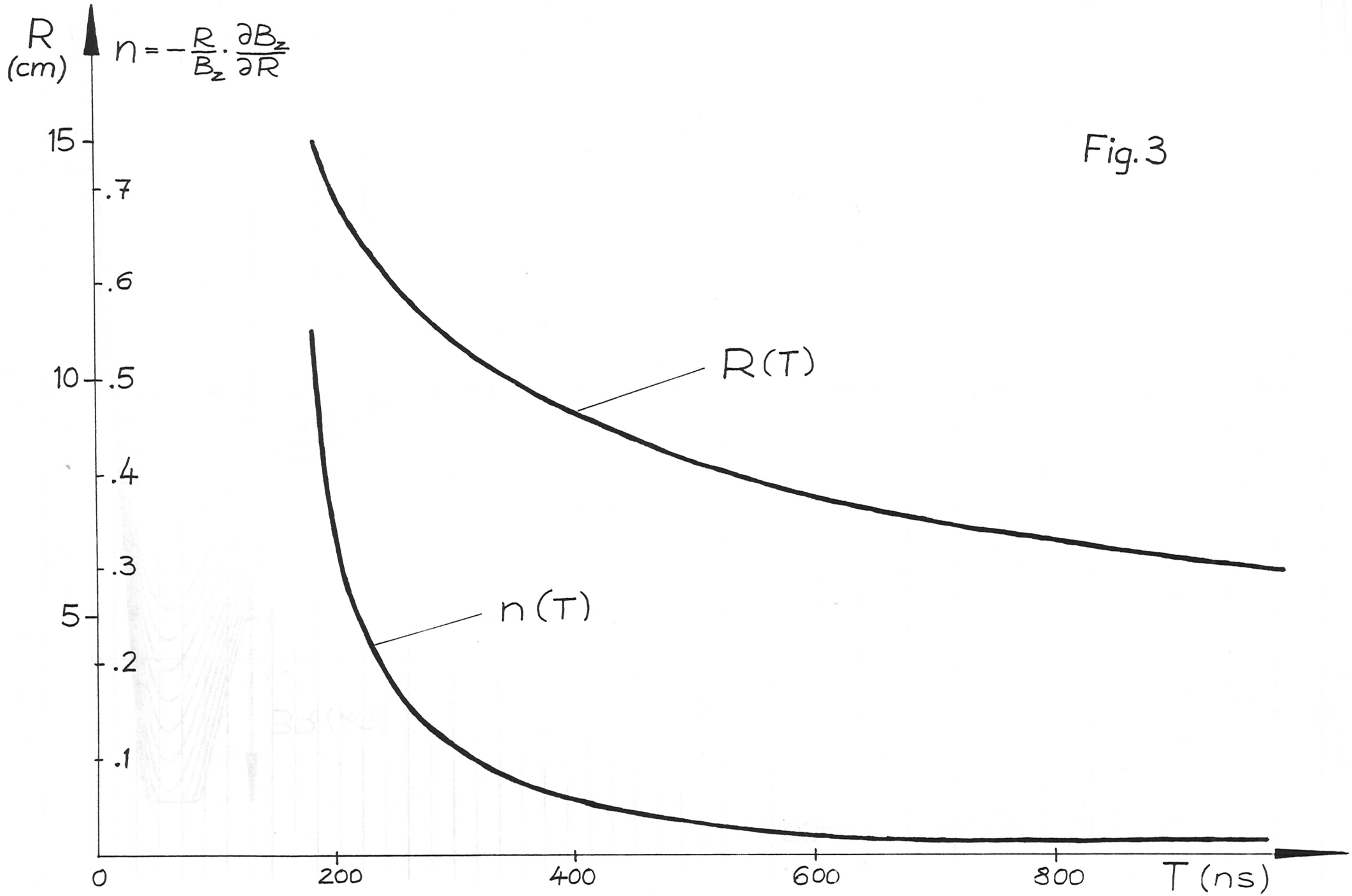
R (cm)
$n = -\frac{R}{B_z} \cdot \frac{\partial B_z}{\partial R}$
15
10
5
.7
.6
.5
.4
.3
.2
.1
R(T)
n(T)
0
200
400
600
800
T (ns)

Fig. 3

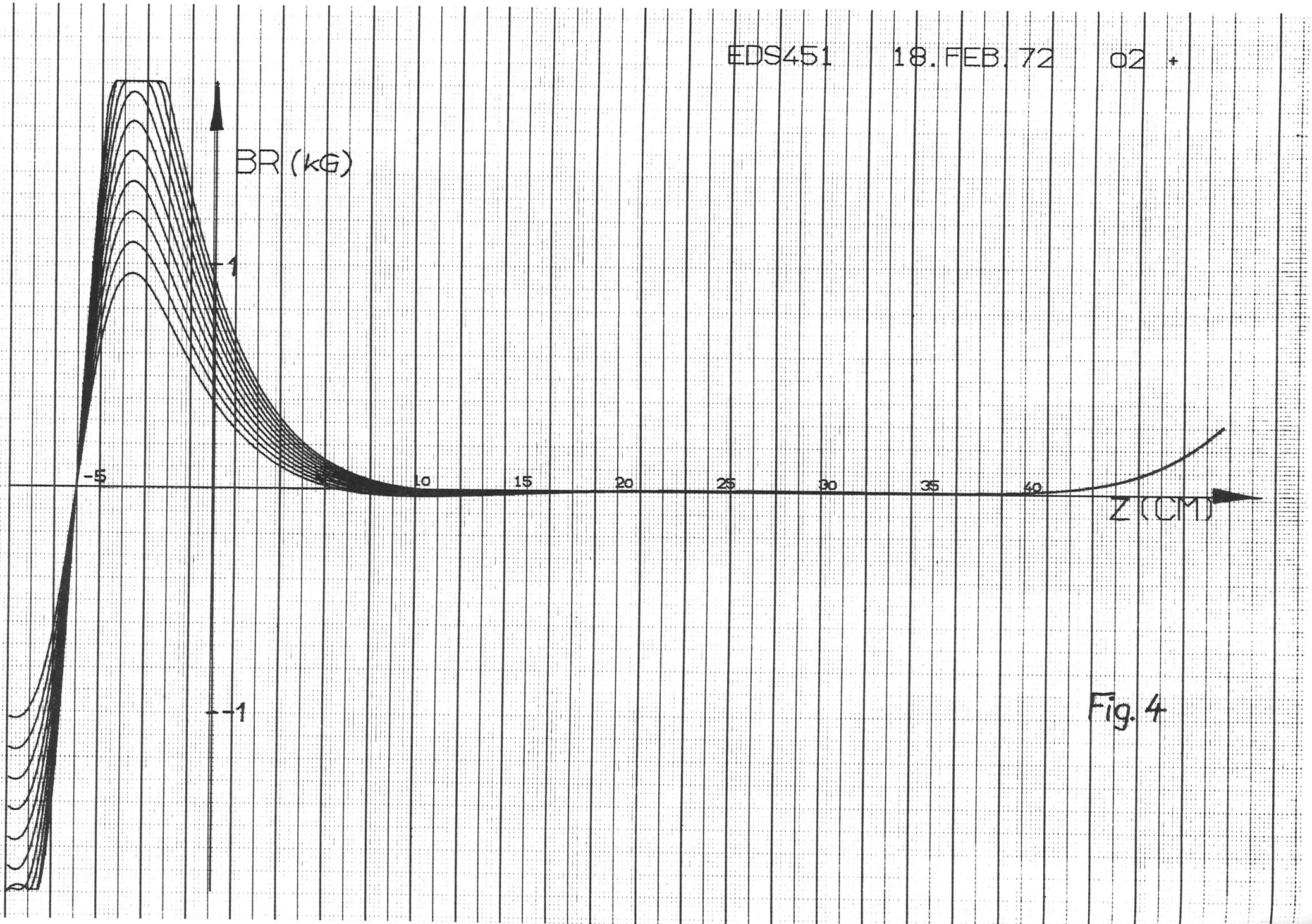

Fig. 4

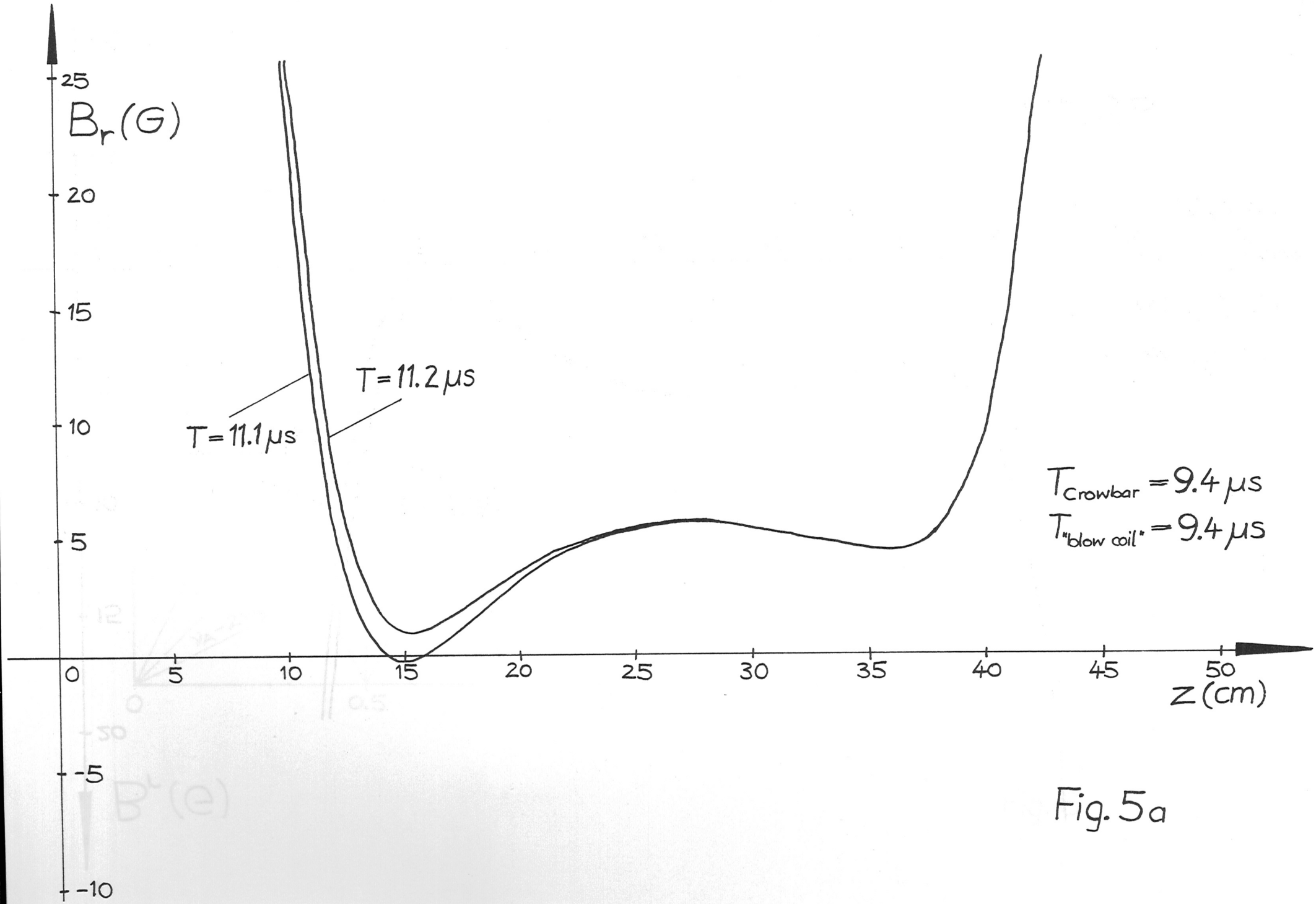
25
$B_r(G)$
20
15
10
5
-5
-10
$T = 11.2\,\mu s$
$T = 11.1\,\mu s$
$T_{Crowbar} = 9.4\,\mu s$
$T_{"blow\ coil"} = 9.4\,\mu s$
0
5
10
15
20
25
30
35
40
45
50
z (cm)

Fig. 5a

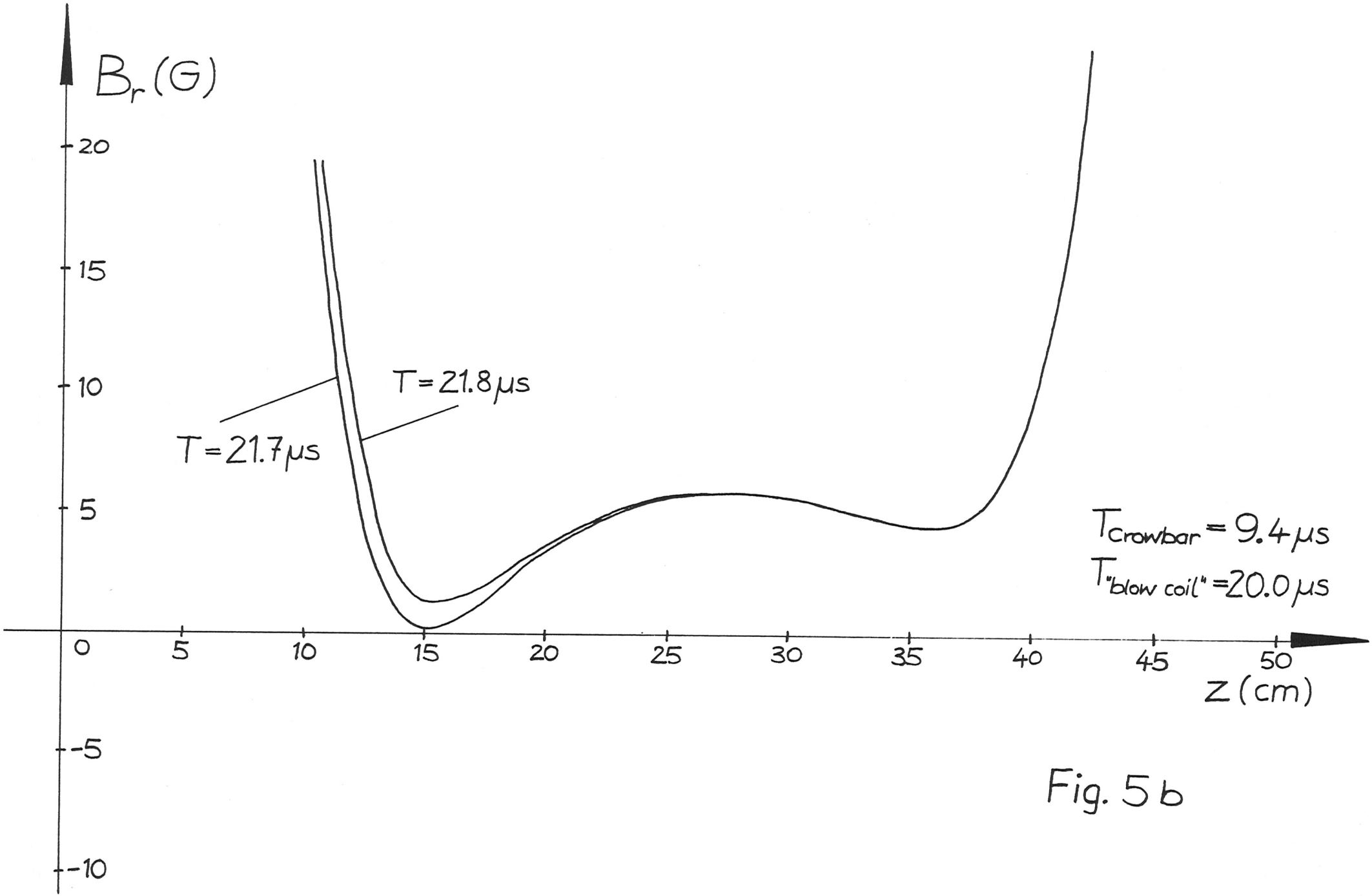
B_r (G)
20
15
10
5
-5
-10
T = 21.8 μs
T = 21.7 μs
$T_{crowbar}$ = 9.4 μs
$T_{"blow\ coil"}$ = 20.0 μs
0
5
10
15
20
25
30
35
40
45
50
Z (cm)

Fig. 5 b

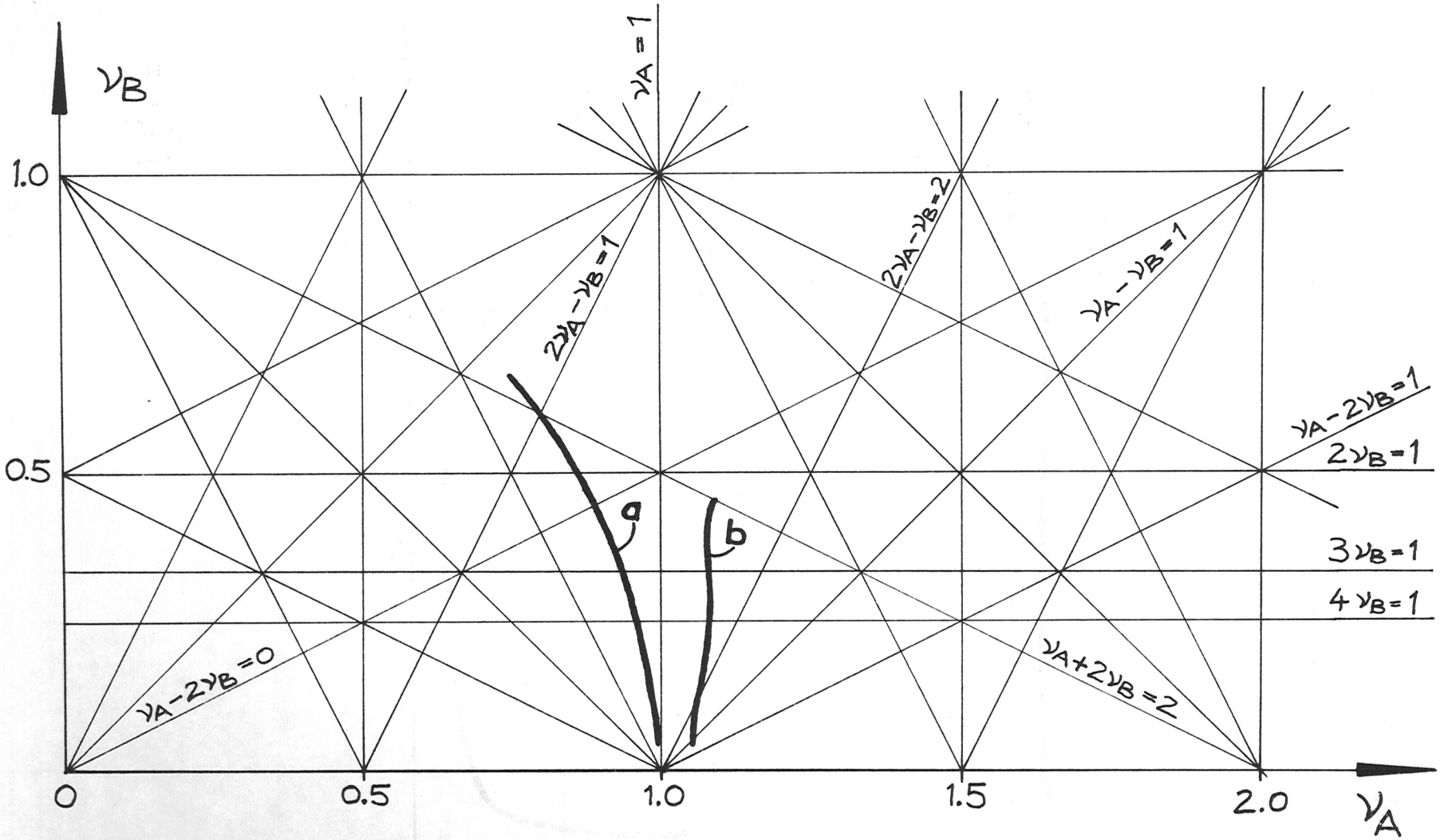
ν_B
1.0
0.5
0
0.5
1.0
1.5
2.0
ν_A
$\nu_A = 1$
$2\nu_A - \nu_B = 1$
$2\nu_A - \nu_B = 2$
$\nu_A - \nu_B = 1$
$\nu_A - 2\nu_B = 1$
$2\nu_B = 1$
$3\nu_B = 1$
$4\nu_B = 1$
$\nu_A - 2\nu_B = 0$
$\nu_A + 2\nu_B = 2$
a
b

Fig. 6

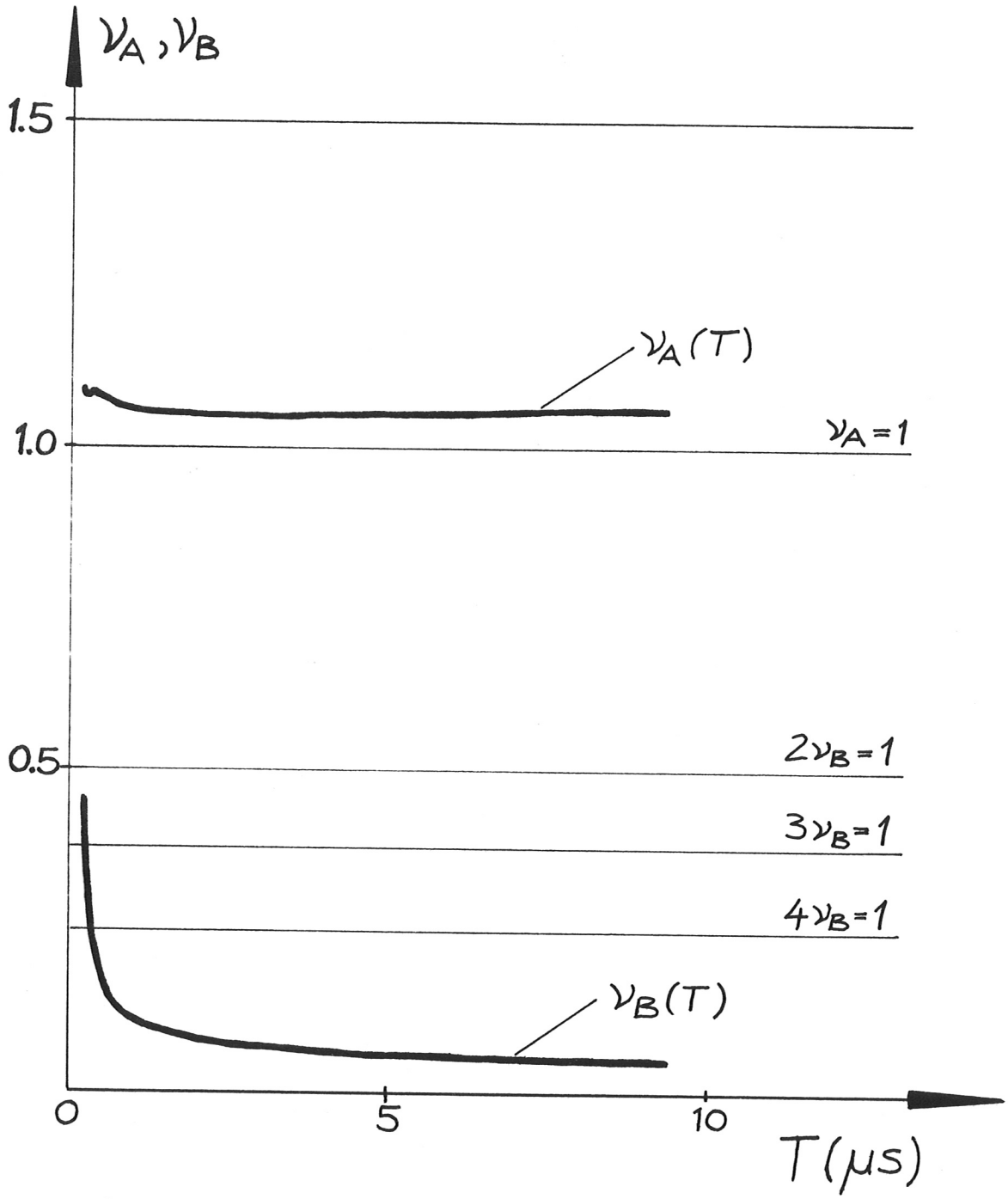

Fig. 7