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CESIUM PLASMA IN THE STELLARATOR WENDELSTEIN WIb

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

REVIEW OF MUNICH ALKALI PLASMA EXPERIMENTS IN TOROIDAL DEVICES +)

D. Eckhartt

In my talk about our experiments on the confinement of alkali plasmas in toroidal devices I would like to give you a chronological review on the lines along which we have been proceeding during the past years. This way I shall end up quite naturally - if time permits - by mentioning our most recent experimental results which will be presented in full detail by Dr. Grieger on Friday morning ++).

Our ideas to study particle losses from Cs plasmas in a stellarator date back to the time of the Salzburg conference in 1961. At that time the situation regarding plasma particle losses across a magnetic field was as follows: in a straight column of highly ionized alkali plasma which was confined radially by a strong magnetic field and axially by electron emitting end plates, measurements of the radial particle density distribution were interpreted as an indication that in these configurations diffusion seemed to proceed according to the predictions of classical theory (1). On the other hand, particle losses in the B-3 stellarator during the Ohmic heating phase were found to be much in excess of what binary collision theory would predict. The anomalously high loss rates could rather well be described by the so-calles "Bohm" diffusion coefficient (2). However, there were certain observations during the afterglow of the stellarator discharge which suggested that plasma currents would induce enhanced diffusion (3). This interpretation later on turned out to be incorrect (4). Nevertheless, at that time and in view of the experimental findings just mentioned it seemed worthwhile to start an experiment in a stellarator using cesium plasma which was believed to show "classical" behavior in a

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+) Paper presented at the International Symposium on Experimental and Theoretical Aspects of Toroidal Confinement, Princeton University, Plasma Physics Laboratory, July 1966.

++) Second paper of this report.

straight machine and could be generated without externally induced currents.

This experiment was performed in 1963 in our WENDELSTEIN device which at that time was equipped with $\ell = 3$ helical windings (5). Let me just briefly sketch the principles of the experimental procedure (Fig. 1). Our machine is a race-track shaped stellarator with an axial length of 319 cm and a tube diameter of 5 cm. The main magnetic field can be pulsed up to 20 kgauss for about one second, but most experiments were performed with 10 kgauss. The $\ell = 3$ helical stabilizing windings along the curved sections yielded a rotational transform of 82^o at the radius of the theoretical aperture of 2.2 cm. The plasma was produced by contact ionization of cesium atoms on a hot tantalum surface about 4 mm in diameter and located on the axis. The tantalum metal was heated by direct passage of current. The heating current was switched off during the time of the experiment and the tantalum piece was allowed to assume its flotating potential. Measurements were made of the total ion input flux, Φ, and of the resulting particle density distribution; the latter was determined by means of a specially developped electrostatic probe. Fig. 2 shows an example of the measured contours of equal particle density. They have a very pronounced central peak at about the position of the plasma source, and an elongated structure in the direction perpendicular to the curvature of the magnetic lines of force. By combining the flux and density measurements into the following relation of steady state:

$$\Phi \cdot \tau = \int n \cdot dV = N ,$$

where N is the total number of ions found in the machine, we can express our results in terms of the mean particle life time, τ. The mean life time was found to be in the order of 10 to 20 ms and was independent of plasma density between 10^{11} and 10^8 particles per cc (5). This value was smaller by one to two orders of magnitude than expected on the basis of classical diffusion. Furthermore, no effect of the helical stabilizing fields could be detected. For these results as well as for the odd shapes of the particle density profiles no simple explanation was apparent. But it was already at that time suspected that the low values of the rotational transform near the magnetic axis - an effect inherent to the $\ell = 3$ type of helical windings - might be of decisive influence on the observed plasma behavior.

Thus, from the point of view of comparing alkali plasmas in a straight and in a curved machine, there were as many open questions as before. We decided, therefore, to make a more direct comparison between the two configurations and to study the influence of the curvature of the magnetic lines of force. This experiment was done by superimposing upon the homogeneous magnetic field in one of our Q-machines a suitable transverse field thus bending the magnetic lines of force to an almost circular shape of variable curvature (6). This experiment, as simple as it looked from the beginning, turned out to be very difficult as regards interpretation of the experimental results. But I may say that we have learned a lot from it, both about plasma equilibrium in a curved magnetic field as well as about alkali plasmas in a Q-machine - I mean plasma production and interaction at the end plates (7). These knowledges were indispensable for the understanding of our further experiments with contact ionization plasmas.

Two effects were found as soon as we turned on the machine and curved the magnetic lines of force:

a) low-frequency drift waves were excited propagating at right angles to the magnetic field (8),

b) additional particle losses appeared that increased with increasing curvature (6).

For some time a connection between these two results was searched for, but could not be confirmed. The observed increase in particle loss rate could rather be attributed to the "lack of equilibrium" in a curved magnetic field (9), that is, the voltage needed to drive the secondary currents in equilibrium in a curved magnetic field establishes an electric field perpendicular to B which gave rise to E x B-drift losses.

The experiment was finally given up since it was proved (6) that "pump-out" losses - if they would appear in this device - should be best distinguishable at such low densities, let us say below about 10^{10} particles per cubic centimeter, that one would have difficulties in obtaining reliable data from probe measurements. Or, in arguing from physical reasons, it was subject to doubt whether the Cs plasma at such low densities would be in thermal equilibrium(10). It is, by the way, from this point of view that we began to be interested in the spectroscopic determination of plasma density in barium plasmas(11).

At about the same time we arrived - by quite different arguments - at the requirement that we should perform our Cs experiments in stellarators, too, at similarly low densities - say below $3 \cdot 10^{10}$ particles per cubic centimeter. This result emerged from an analysis of the "diffusive equilibrium" of a plasma with finite resistivity in a stellarator, where we paid special attention to the balance of the mass flows(12). This analysis was intended to find a "scaling law" through which experiments in hydrogen and cesium could be compared. We arrived at the conclusion that the most sensitive quantity by which the equilibrium properties of two experiments should be compared was the magnitude of the velocity of the balancing mass flow parallel to B. This velocity cannot exceed the thermal velocity of the ions, since the only force available to drive a mass motion in this direction is a pressure gradient. For a given machine the magnitude of the mass flow can be reduced by reducing the particle density.

With these restrictions in mind, one would be led to the conclusion that in real experimental situations in a stellarator, it would be quite difficult for the plasma to adjust itself to this complicated system of secondary currents and balancing mass flows with all velocities small compared to the thermal velocity so that inertia need not be considered. In particular this would be the case for the low values of the rotational transform one would expect for a $\ell = 3$ system near the magnetic axis, since the balancing mass flows were found to be inversely proportional to the third power of the angle of rotational transform, ι(12). Thus, the observed high particle loss rates might as well be an expression of incomplete plasma equilibrium, incomplete in the sense of the model of the afore mentioned analysis.

As it are the secondary currents along the magnetic lines of force which - in a plasma of finite resistivity - produce the voltage drop responsible for the mass flow it was quite obvious that one should look out for a way of reducing these secondary currents or of avoiding them at all. For some time we, therefore, spent a lot of thinking about a "scalloped" machine (13). But this scheme would not yield any considerable reduction in the magnitude of the secondary currents. We decided finally to devote ourselves to a toroidal arrangement with purely poloidal magnetic fields where, a priori, no secondary currents were needed in equilibrium (14). This configuration would be most suitable for studying the role of secondary currents in toroidal machines. Along these arguments we arrived at an octopole device similar to that of KERST (15) and OKHAWA (16), where the particular magnetic field line pattern excluded flute-type instabilities in accordance with the "mean minimum-B principle".

Thus, at the beginning of the last year, 1965, our experimental program was to investigate particle losses of Cs plasmas in an $\ell = 2$ stellarator and to compare the stellarator results with the ones obtained in the octopole. In particular, we aimed at a decisive answer to the question, whether Bohm-type losses were a universal phenomenon and would occur in both types of toroidal machines irrespective of the existence of secondary currents. In order to obtain a clear distinction between "classical" particle losses, like resistive diffusion, surface recombination at the source, etc., on the one hand, and Bohm-type losses, on the other, we intended to adjust our experimental conditions - and even the parameters of the future octopole device (14) - in such a way that Bohm-type losses - if they would appear - should surpass all other known types of particle losses by at least one order of magnitude.

We presented our results at the Culham conference last fall (17). As for the octopole, our results yielded a relationship between ion input flux and particle density which excluded the occurrence of Bohm-type losses and could be explained by particle losses on the supports of the ring conductors in the plasma. The experimental finding that these results could only be obtained by superimposing a comparatively weak toroidal magnetic field upon the poloidal octopole field requires closer investigation. This will be done in our group.

As for the $\ell = 2$ stellarator, the answer to the question whether or not Bohm-type losses would govern the relationship between input flux and resulting particle density in our device was clearly: no. This may be seen from Fig. 3. Here we have computed the relationship between input flux, Φ, and mean particle density, N/V, by assuming that the plasma transport across the confining field proceeds according to classical diffusion and that the particles are lost by surface recombination on the supports of the plasma source. The calculated values are represented by the lower curve of the shaded area in Fig. 3; the upper curve includes an estimation of particle recombination on the source. The crosses represent the experimental values. Curve Φ_{re} gives the flux across the confining field by assuming resistive diffusion alone, and no recombination at the surfaces of the obstacles inside the plasma. Curve Φ_p represents the connection between input flux and mean particle density, if Bohm-type losses would be present in the machine. The two open circles stand for our old measurements in 1963 with the $\ell = 3$ type windings and for new measurements without any stabilizing fields at all.

After having shown that in the $\ell = 2$ stellarator, under the conditions of our experiment, Bohm-type losses did not occur, we were, of course, interested to prove in a more direct manner, whether the particle transport across the magnetic field would follow the laws of resistive diffusion or not. For this purpose, the ratio between the two loss mechanisms: surface recombination at the supports of the plasma source and its current leads, to: plasma motion across the magnetic lines of force and subsequent recombination on the wall of the vacuum vessel, had to be sensitively reduced. This was done in our latest experiments, where the tantalum surface acting as plasma source had the shape of a small ball and was hung from a very thin tungsten wire. It was heated by means of bombardment with a beam of energetic electrons from a gun outside the plasma.

From the same arguments - namely to avoid as far as possible any recombining surfaces inside the plasma volume - the use of our usual probes could no longer be tolerated. Therefore, only the value of the central plasma density inside the region connected by magnetic field lines to the source was determined with cylindrical Langmuir probes of minimum diameter. This central density was related to the radial particle flux which could be directly measured by a special detector located at the edge of the aperture.

Let me briefly summarize what we found: within a certain range of plate temperatures - the limits which we can account for - and within the range of technically available parameters like the strength of the main field, the magnitude of ι, densities up to 10^{10}, we observed the relationship between central particle density and radial particle flux across the magnetic field to be described by the coefficient of resistive diffusion multiplied by the factor $(1+\frac{4\pi^2}{\iota^2})$, as one would expect for a stellarator $^{(12,18)}$. In addition, we were able to recover our last year's findings, namely the sensitive dependence of the central particle density upon the correction fields, i.e. upon the relative position of the magnetic axis and the plasma source. Furthermore, we could observe the sudden reductions in particle density as the input flux approaches certain critical values.

More details about this experiment will be given on Friday, as I already have told you.

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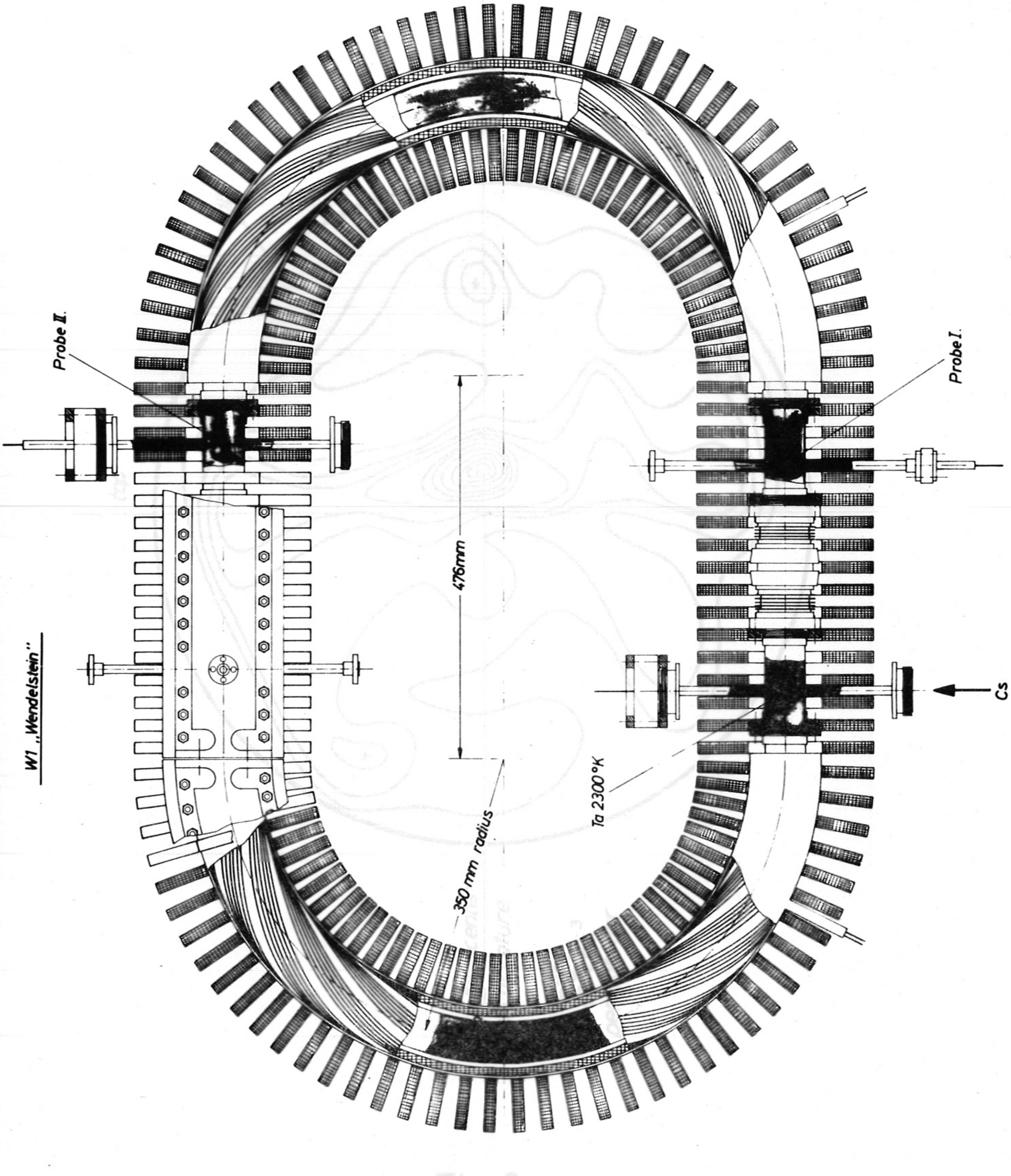

W1 „Wendelstein“
Probe II.
Probe I.
476mm
350 mm radius
Ta 2300°K
Cs

Fig. 1

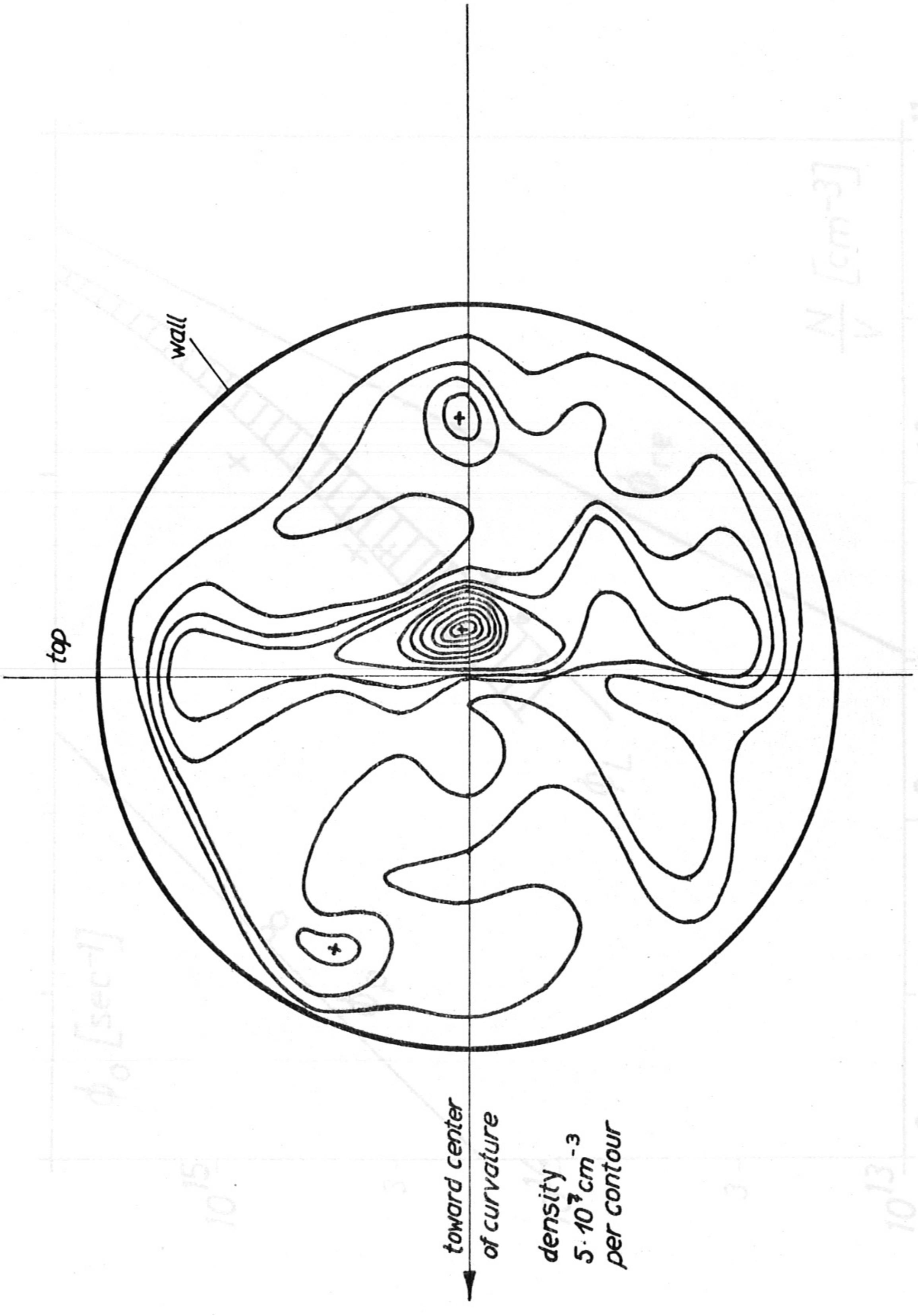
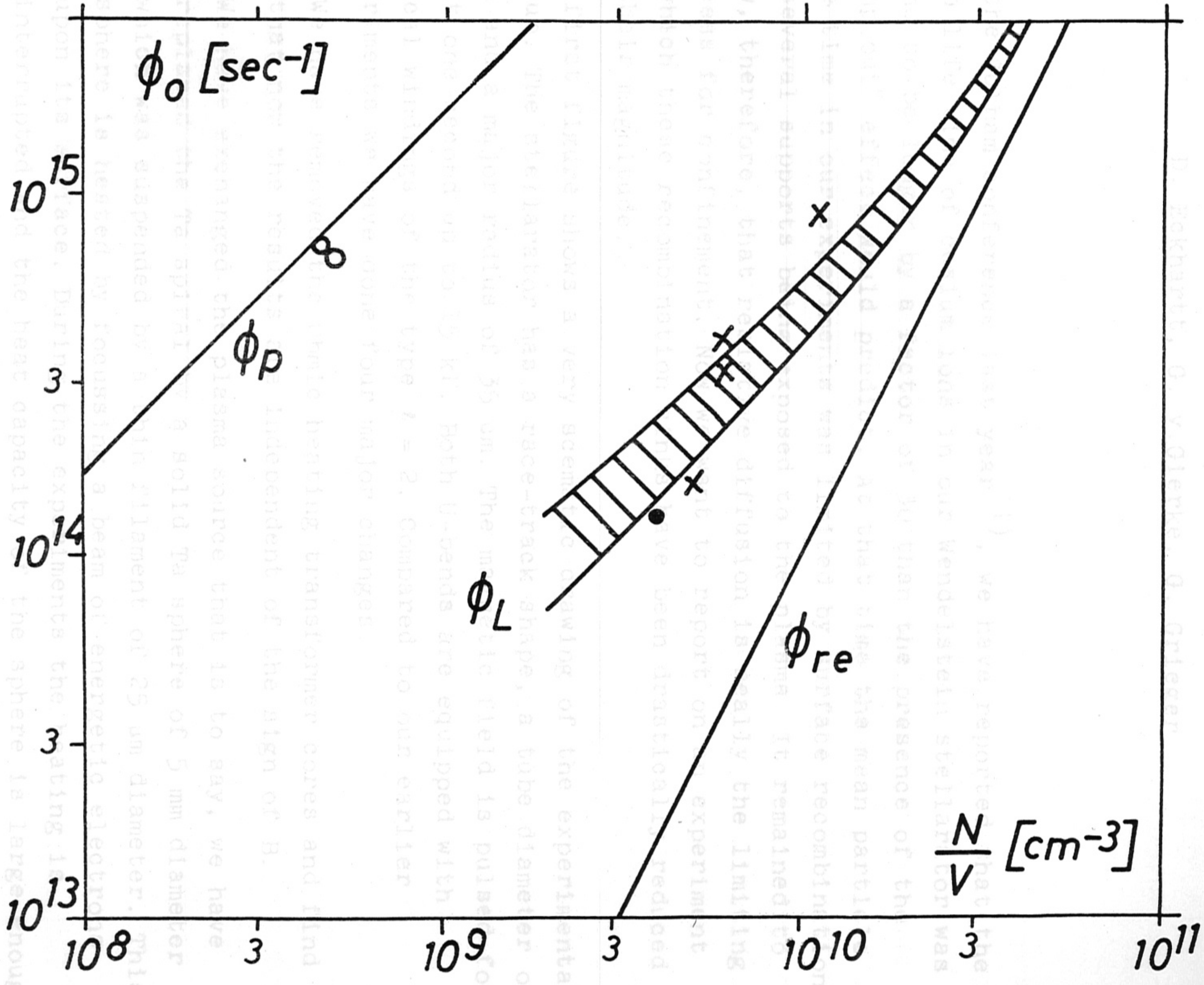

wall
top
toward center of curvature
density $5\cdot10^{7}\,cm^{-3}$ per contour

Fig. 2



CESIUM PLASMA IN THE STELLARATOR WENDELSTEIN WIb [+)]

D. Eckhartt, G. v.Gierke, G. Grieger

At the Culham conference last year 1), we have reported that the mean life time of cesium ions in our Wendelstein stellarator was found to be longer by a factor of 30 than the presence of the "pump out" effect would predict. At that time the mean particle life time in our experiments was limited by surface recombination on several supports being exposed to the plasma. It remained to show, therefore, that resistive diffusion is really the limiting process for confinement. Now we want to report on an experiment in which these recombination sinks have been drastically reduced in their magnitude.

The first figure shows a very scematic drawing of the experimental set up. The stellarator has a race-track shape, a tube diameter of 5 cm and a major radius of 35 cm. The magnetic field is pulsed for about one second up to 15 kΓ. Both U-bends are equipped with helical windings of the type $\ell = 2$. Compared to our earlier experiments we have done four major changes.

1) We have removed the Ohmic heating transformer cores and find that now the results are independent of the sign of B.
2) We have exchanged the plasma source that is to say, we have replaced the Ta spiral by a solid Ta sphere of 5 mm diameter which was suspended by a thin filament of 25 μm diameter. This sphere is heated by focussing a beam of energetic electrons upon its surface. During the experiments the heating is interrupted and the heat capacity of the sphere is large enough to yield a constant ion input flux over more than three seconds.

+) A combination of two papers presented by G. Grieger at the International Symposium on Experimental and Theoretical Aspects of Toroidal Confinement, Princeton University, Plasma Physics Laboratory, July 1966, and the First European Conference on Controlled Fusion and Plasma Physics, Munich, October 1966.

This is synonymous with saying that during this time an electron sheath can be maintained on the emitter which is of important influence on the experimental results.

3) The double-double probes used so far will no longer give reliable results since resistive diffusion is so slow that most of the ions will recombine on the shields of the probe instead of being detected. Therefore these two probes - one of them located near to the emitter, the other one on the far side of the apparatus (see Fig. 1) - have been replaced by cylindrical probes consisting of thin wires, 50 μm in diameter, which - apart from the tip - are insolated by a glass coating of about 10 μm thickness. The probes have to be chosen so small in order to measure the mean particle density instead of the input flux density.

   In order to get reliable results it is necessary that the probes are located on such magnetic lines which pass through the emitter so that small changes of the sheath voltage at the emitter can provide electron balance. Furthermore, they have to be biased with respect to the emitter and the whole system - emitter and probes - must be allowed to flote with respect to the metallic wall, otherwise the results might be drastically changed.

4) Near the position of the far probe an annular particle detector was placed. This detector limits the plasma radius to 1.5 cm by its open area. Particles which have left the so defined plasma volume can be detected by this system if they move along the magnetic lines towards its surface.

With these devices in place we have measured the following quantities:

1) The total input flux of ions.
2) The mean particle density at two different positions, one near the source, the other one about 150 cm far from it.
3) The flux of particles arriving at the annular detector.

These informations provide three independent checks of the diffusion mechanism. For this purpose we have solved the diffusion equations for the two candidats, resistive diffusion and Bohm diffusion and have obtained relations between the center plasma density, n_o, and the flux, Φ , of the diffusing particles. (In these particular calculations losses due to surface recombination have been neglected. Calculations which take this effect into account yield only slightly different results.) In case of resistive diffusion one gets

$$\Phi_{re} = 2.8 \cdot 10^{-7} \frac{n_o^2}{B^2} \left(1 + 4 \frac{\pi^2}{\iota^2}\right) \qquad [B] = k\Gamma$$

and in case of "Bohm" diffusion

$$\Phi_B = 0.94 \cdot 10^6 \frac{n_o}{B} .$$

The first check is based on a comparison of the density measured by the two probes at different distances from the source. In Fig. 2 we have plotted the ratio of signal detected by the far probe to the one detected by the near probe as a function of B. In case of resistive diffusion this ratio is expected to be nearly equal to one as shown by the upper of the two solid curves +). Bohm diffusion, however, is so fast and the aperture of our stellarator so small that a rapid decay of n away from the source would be the consequence. This behaviour is indicated by the lower curve. The experimental results (crosses) agree with resistive diffusion but disagree with Bohm diffusion. It should be emphasized that this result is based on the ratio of two probe signals and thus independent of probe sensitivity. In order to eliminate differences in the sensitive area of the two probes, they have been exchanged in position.

The second check is concerned with the annular particle detector and uses very similar arguments as the preceding one. In case of resistive diffusion the radial motion of the plasma is so slow compared to the ion thermal velocity that practically all of the

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+) It should be mentioned that the theoretical curves shown in this and all the following figures represent absolute values and no parameter is available for adjustment.

particles diffusing out of the plasma volume should hit the particle detector. In case of Bohm diffusion, however, the radial motion is so fast that only those particles which leave the plasma volume within ± 5 cm axial distance from the position of the detector - and these are only 3 % of the total - have a chance to be detected. The others should be lost to the wall.

The flux measured by the particle detector represents about 50 % of the total input flux. The rest of the input flux can be assumed to be lost due to surface recombination on the emitter and on the probes as well. This result means that practically all of the particles leaving the plasma by diffusion in radial direction are found on the annular detector and this is in contradiction to the assumption of Bohm diffusion.

The third check is based on the relation between the central particle density, n_o, and the flux collected by the annular detector. We have not yet been able to decide the question whether the diffusion is proportional to $\frac{1}{B^2}$ or to $\frac{1}{B}$ since the scattering of the experimental points is too large and the range over which the magnetic field could be varied too small. What we could do was to keep the main magnetic field constant and measure the dependence of the loss rates on ι, the angle of rotational transform. This is shown in Fig. 3. One sees qualitative and quantitative agreement with the curve for resistive diffusion as long as ι is not too small (low ι-limit for equilibrium). There are several orders of magnitude disagreement with the curve for Bohm diffusion.

In Fig. 4 the total magnetic field is kept constant and the dependence of the radial flux on the central particle density is plotted. It is observed that this flux is proportional to n_o^2 and the experimental points fit the theoretical curve for resistive diffusion. There is no agreement with the curve expected for Bohm diffusion, in which case Φ should be proportional to n_o instead of n_o^2.

Therefore, we believe that we could show that radial particle losses of a Cs plasma in a stellarator of the type used here are determined by resistive diffusion rather than by Bohm diffusion provided one important condition is satisfied and that is that the plasma is able to thermalize.

This is apparent from Fig. 5 where the relative loss rate of particles versus the emitter temperature is plotted. For this particular set of parameters only within the range of 1800 to 2200°K we observe a quiescent plasma which then shows the behaviour as described before. (Again the dotted curve is calculated for resistive diffusion.) But not only lowering but also increasing the temperature of the emitter above 2200°K yields a rapid increase of the relative loss rates by more than two orders of magnitude +). We tentatively explain this the following way: If the experiment starts the particle density is extremely low. In this case a strong electron sheath is present at the emitter by which all filling ions gain energy. The distribution function of these filling ions is then a Maxwellian with a temperature equal to the emitter temperature but only the high energy tail above the sheath energy is populated thus representing two counterstreaming ion beams. The mean velocity of these beams is increasing with increasing temperature. Whether a quiescent plasma will then build up itself is a question whether or not diffusion in velocity space is fast enough as compared to the particle loss rate so that the whole distribution function can be filled up. As will be seen, this question can be reduced to the following one, namely under which conditions the just mentioned ion beams become unstable due to two beam instabilities. This is exactly the problem treated by FRIED and WONG 2) and their results are used in Fig. 7. There the instability limits are plotted in a frame: ratio of beam density to the density of thermal ions vs. the square root of sheath voltage to thermal voltage. The upper curve is valid for ion temperature equal to emitter temperature and the lower one for the ion temperature somewhat higher than the emitter temperature. The curve applicable to our experiments should be found within the neighbourhood of the lower curve since all ions gain some energy from the radial component of the electric field 3).

+) In this connection it should also be mentioned that the half-width of the correction fields yielding thermalization is the narrower the higher the temperature. This behaviour is shown in Fig. 6.

The dotted line is a steady state solution assuming that only collisions are active but instabilities absent. The experimental result as plotted in Fig. 5 show that the plasma is quiescent up to the value of the sheath voltage marked by a star within Fig. 7 whereas above this point largely increased particle loss rates are observed. This behaviour is not immediately apparent from these curves since an intersection of the dotted line with this instability limit is found at much higher values of the sheath voltage. However, we have to remember that the dotted line represents a steady state solution and in the initial phase of the experiment the ratio of beam to thermal ion density is much larger than shown by this curve and the instability limit might be reached. If this happens we have zo discuss the influence of the instability on the thermalization time. One would expect that, if there is any such influence, it should even lead to an enhanced thermalization. But every such mechanism leading to enhanced thermalization must then lead also to an enhanced diffusion so that these considerations together with the experimental result lead to the conclusion that the instability, if it appears in the initial phase of the experiment, is obviously accompanied by so large particle loss rates that the conditions for the occurance of the instability are maintained throughout the whole duration of the experiment, and that although for these parameters also the existence of a quiescent plasma should be possible.

But these are already hypotheses since we have not yet studied in enough detail this transition from a stable to a n apparently unstable case. This will be one of the points of our future program since the results might throw some light on the nature of the different loss mechanisms involved at least for a stellarator of this particular type used in these experiments.

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Figure Captions

Fig. 1 Scematic drawing of the stellarator Wendelstein WIb.

Fig. 2 Ratio of signals detected by the distant probe and the near probe vs. the magnetic field.

Fig. 3 Relative loss rate of particles (i.e. radial loss flux of particles devided by the square of the central particle density) vs. $4\frac{\pi^2}{\iota^2}$.

Fig. 4 Central particle density vs. flux of diffusing particles.

Fig. 5 Relative loss rate of particles vs. emitter temperature.

Fig. 6 Width of the correction fields yielding half of the optimum central density vs. emitter temperature.

Fig. 7 Instability limits given in a frame beam density over density of thermal ions vs. $\sqrt{u_s/u_{th}}$ (u_s being the sheath voltage at the emitter, $u_{th} = kT/e$). The dotted line represents a steady state solution for $n_b/n_o = f(\sqrt{u_s/u_{th}})$ in case that only collisions are active and instabilities absent.

In Fig. 2 - 5 two solid curves, a and b, represent theoretical loss rates according to the equations given on page 3 of this report, curve "a" for resistive diffusion and curve "b" for Bohm-diffusion.

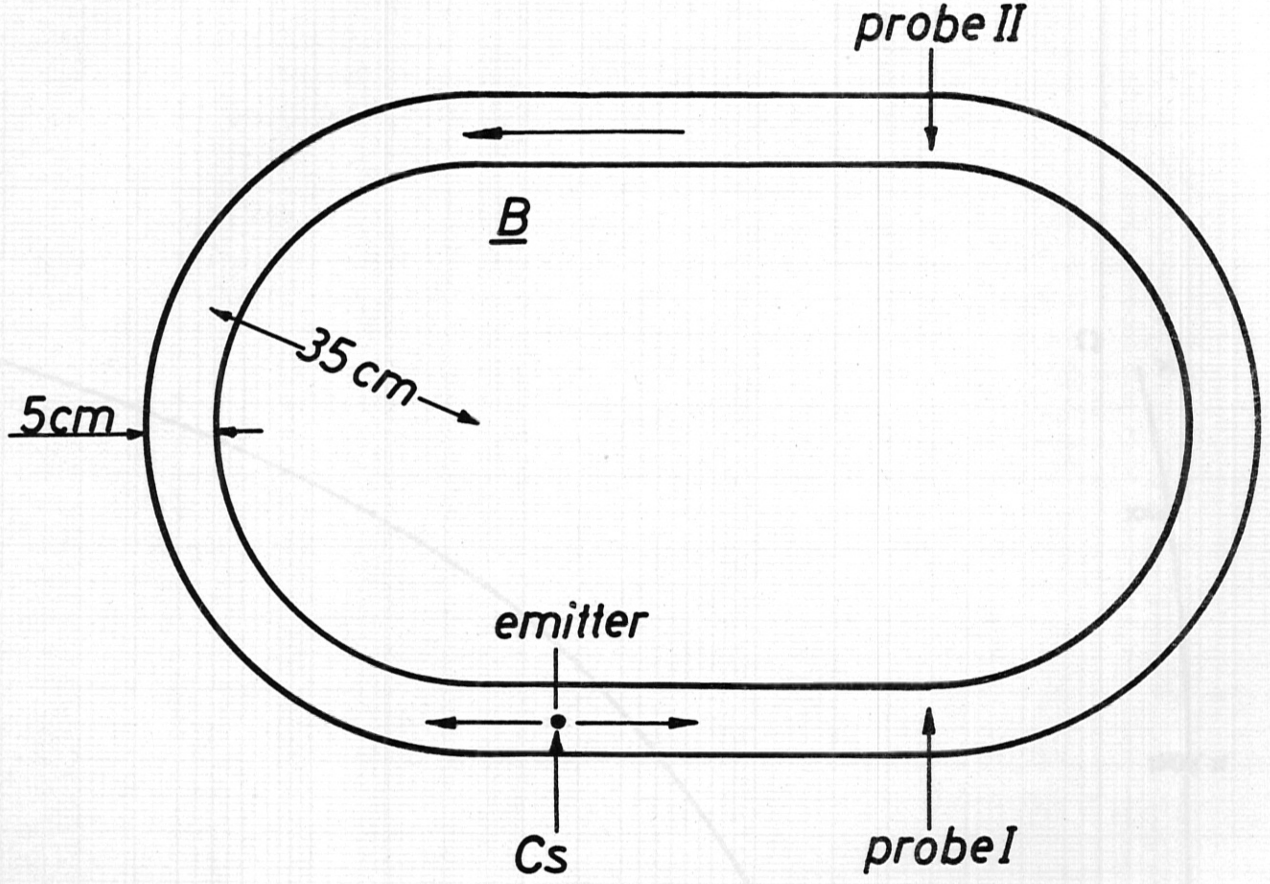

Fig. 1

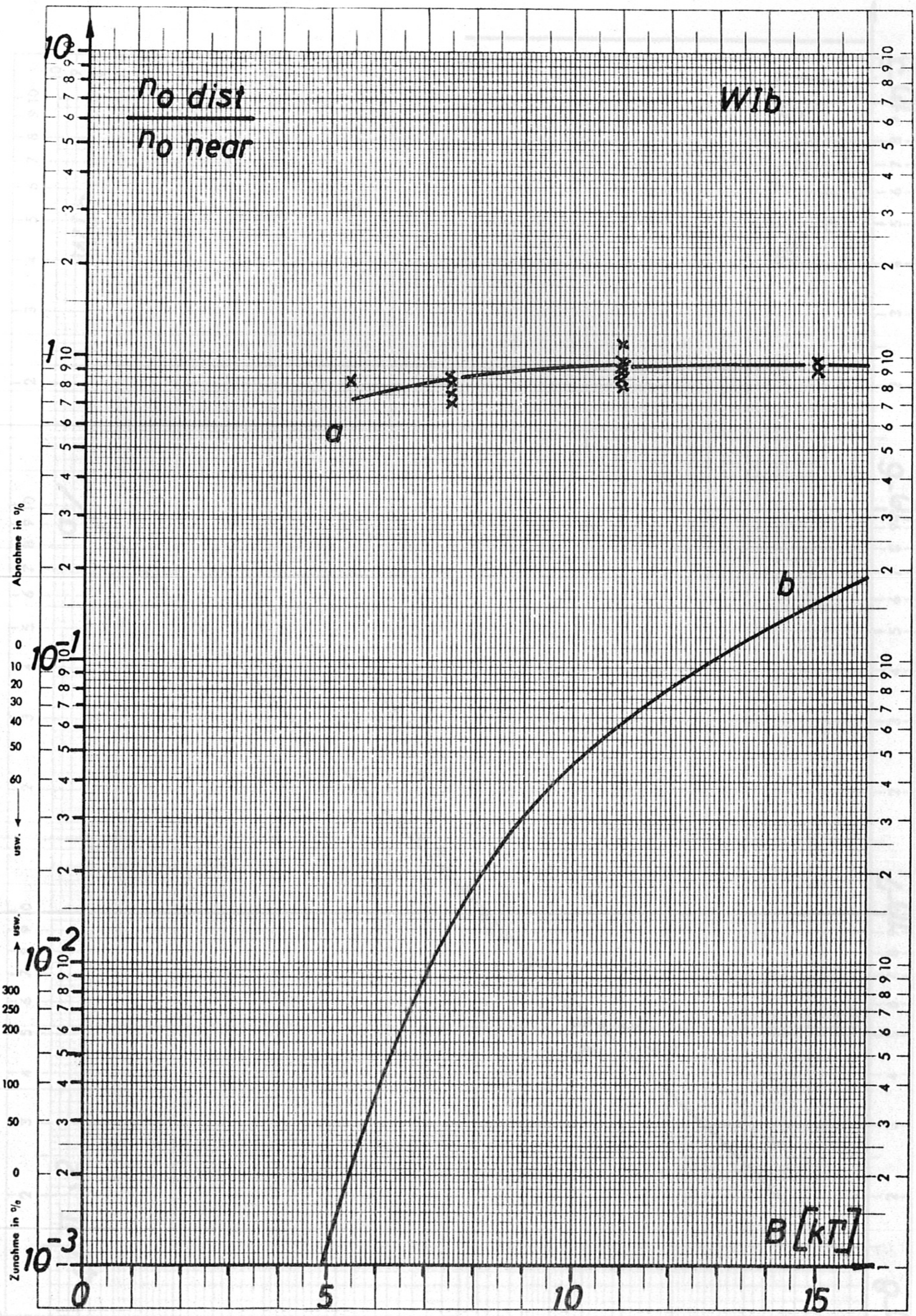
10
1
10⁻¹
10⁻²
10⁻³
n_o dist
n_o near
WIb
a
b
B [kT]
0
5
10
15
Abnahme in %
Zunahme in %
usw.

Fig.2

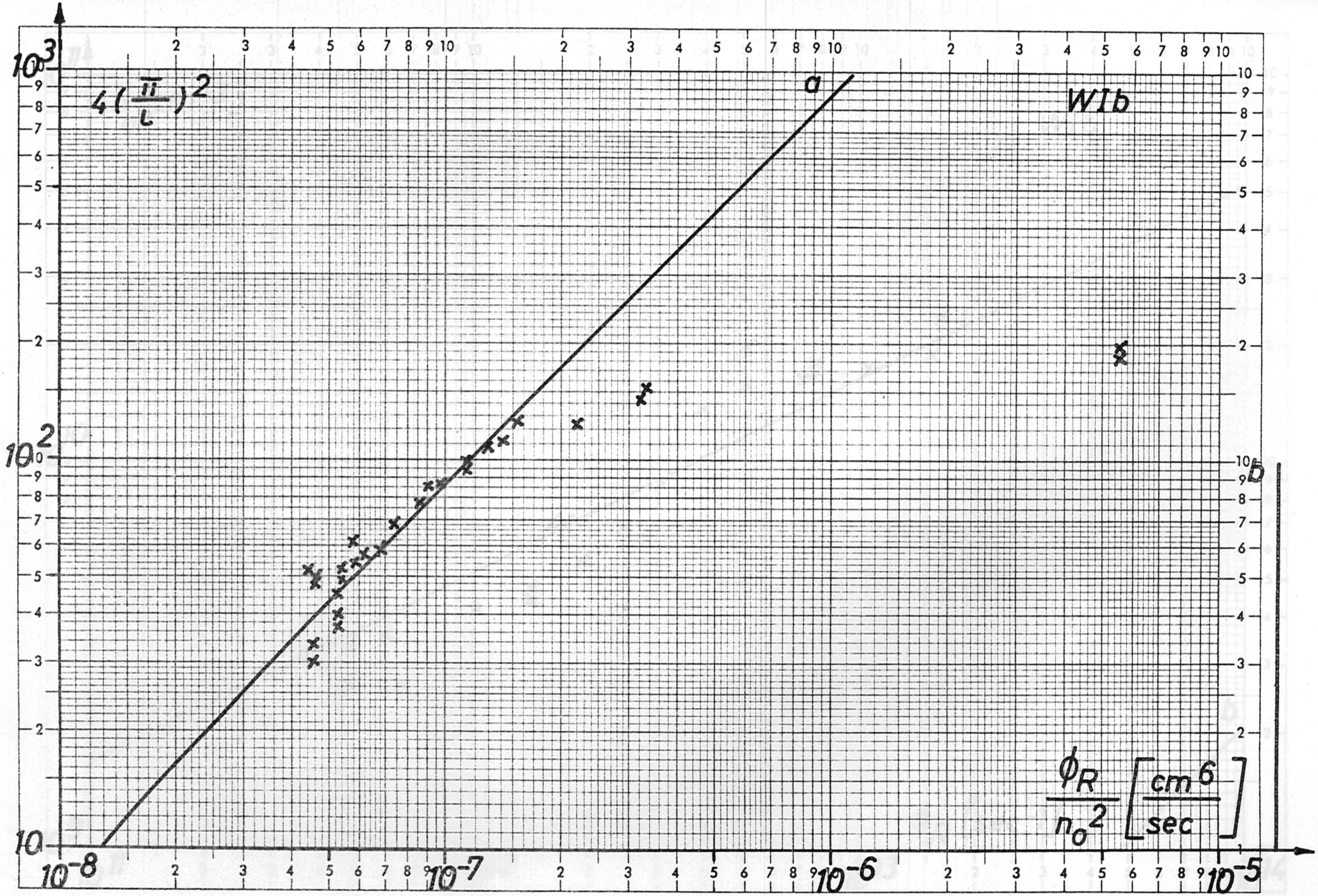
10^3
$4(\frac{\pi}{L})^2$
a
WIb
10^2
b
10
10^{-8}
10^{-7}
10^{-6}
10^{-5}
$\frac{\phi_R}{n_o^2}\left[\frac{cm^6}{sec}\right]$

Fig. 3

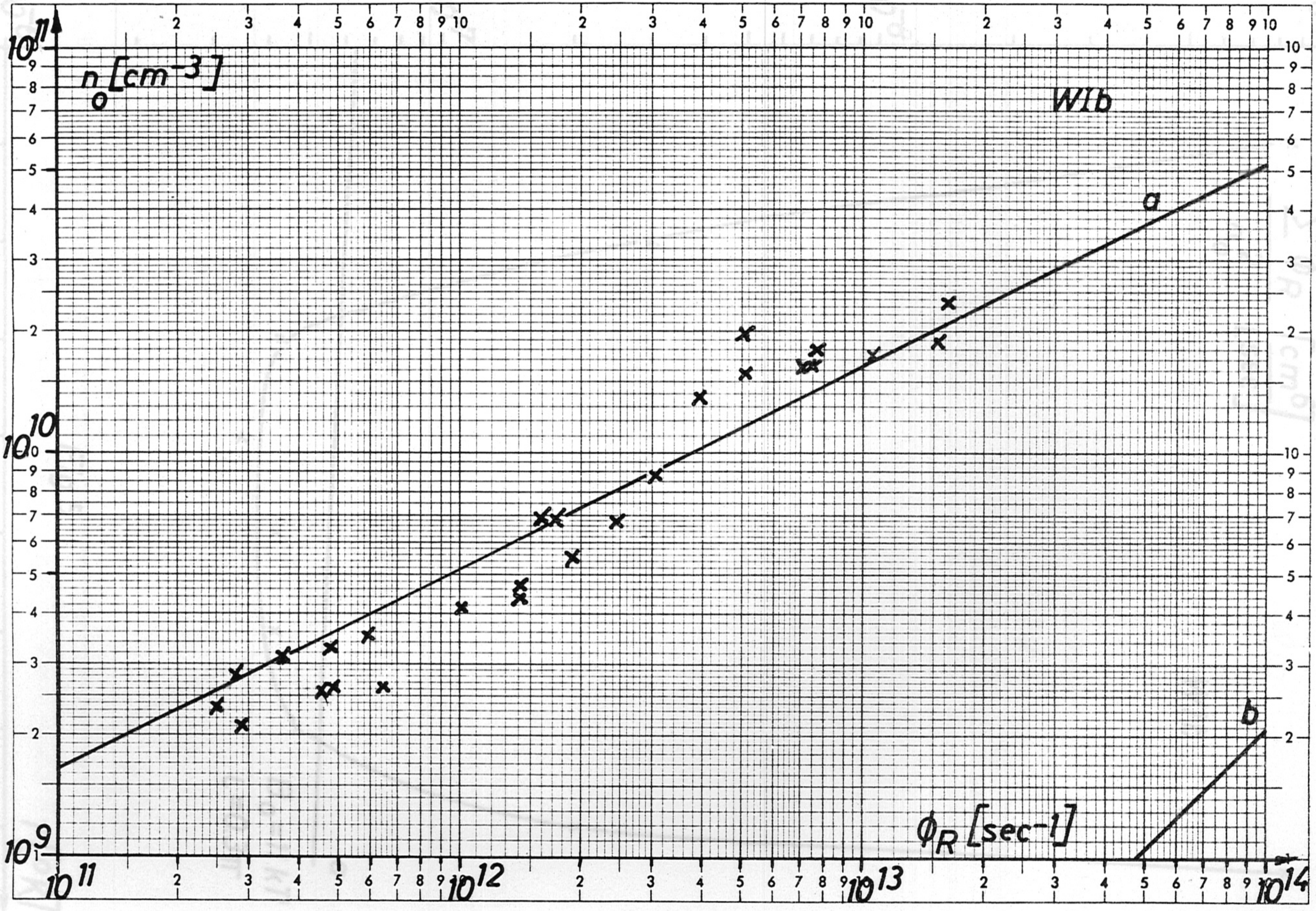

Fig.4

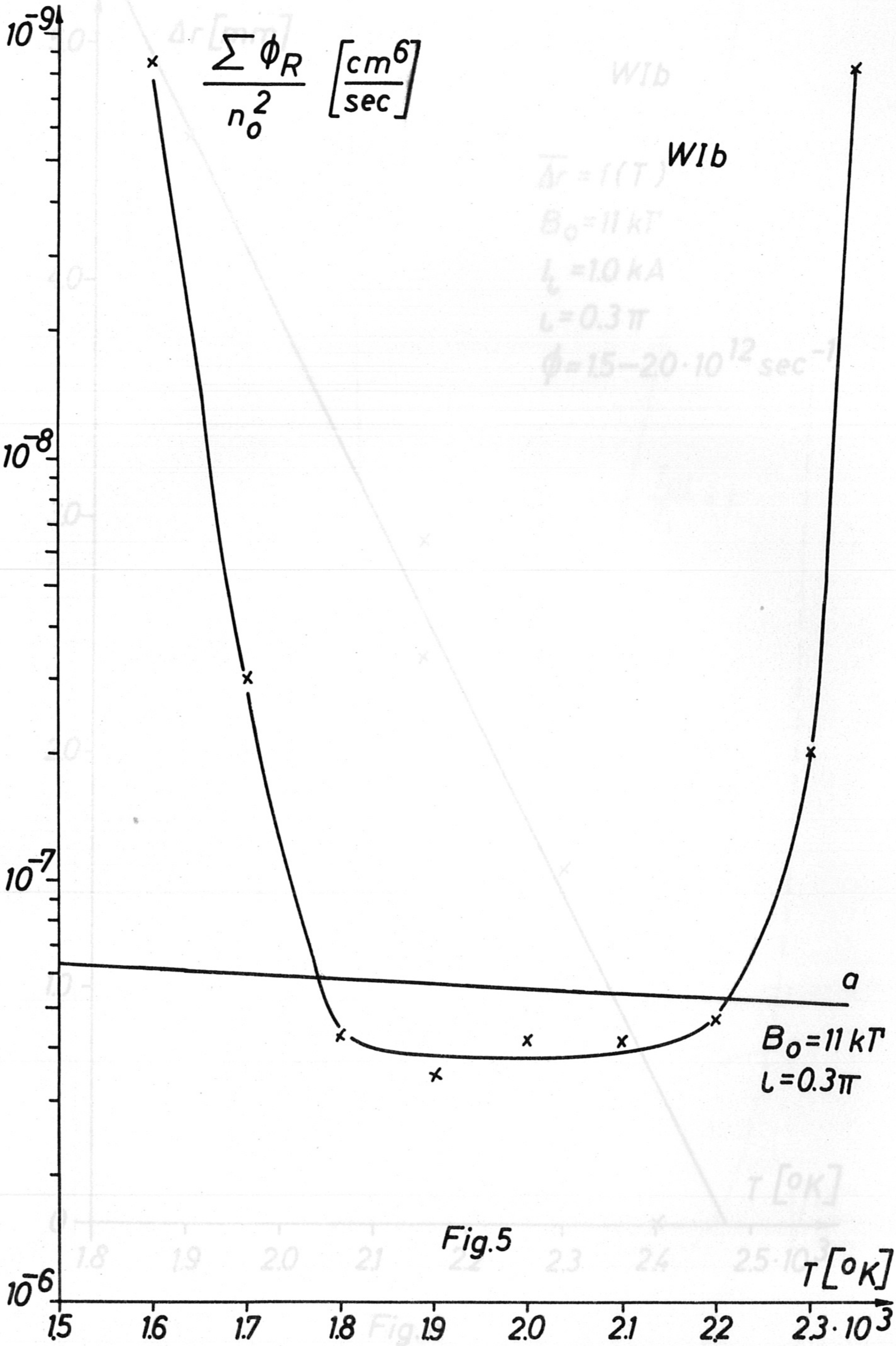
$\frac{\sum \phi_R}{n_o^2}$ $\left[\frac{cm^6}{sec}\right]$
WIb
10^{-9}
10^{-8}
10^{-7}
10^{-6}
a
B_o=11 kT
ι=0.3π
T [°K]
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
$2.3 \cdot 10^3$

Fig.5

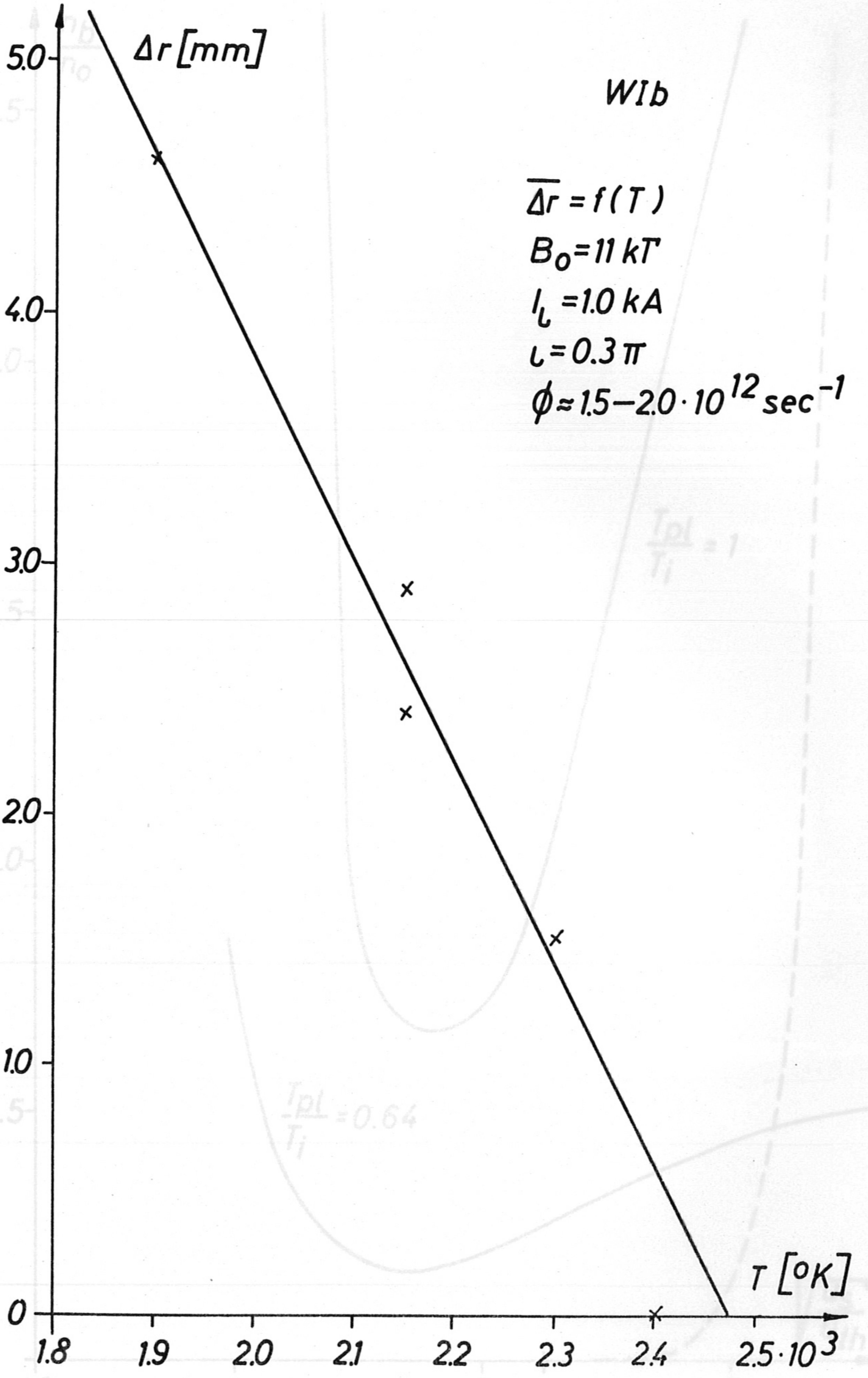
Δr [mm]
5.0
4.0
3.0
2.0
1.0
0
WIb
$\overline{\Delta r} = f(T)$
$B_0 = 11$ kT
$I_\iota = 1.0$ kA
$\iota = 0.3\pi$
$\phi \approx 1.5 - 2.0 \cdot 10^{12}$ sec^{-1}
T [°K]
1.8
1.9
2.0
2.1
2.2
2.3
2.4
$2.5 \cdot 10^3$

Fig. 6

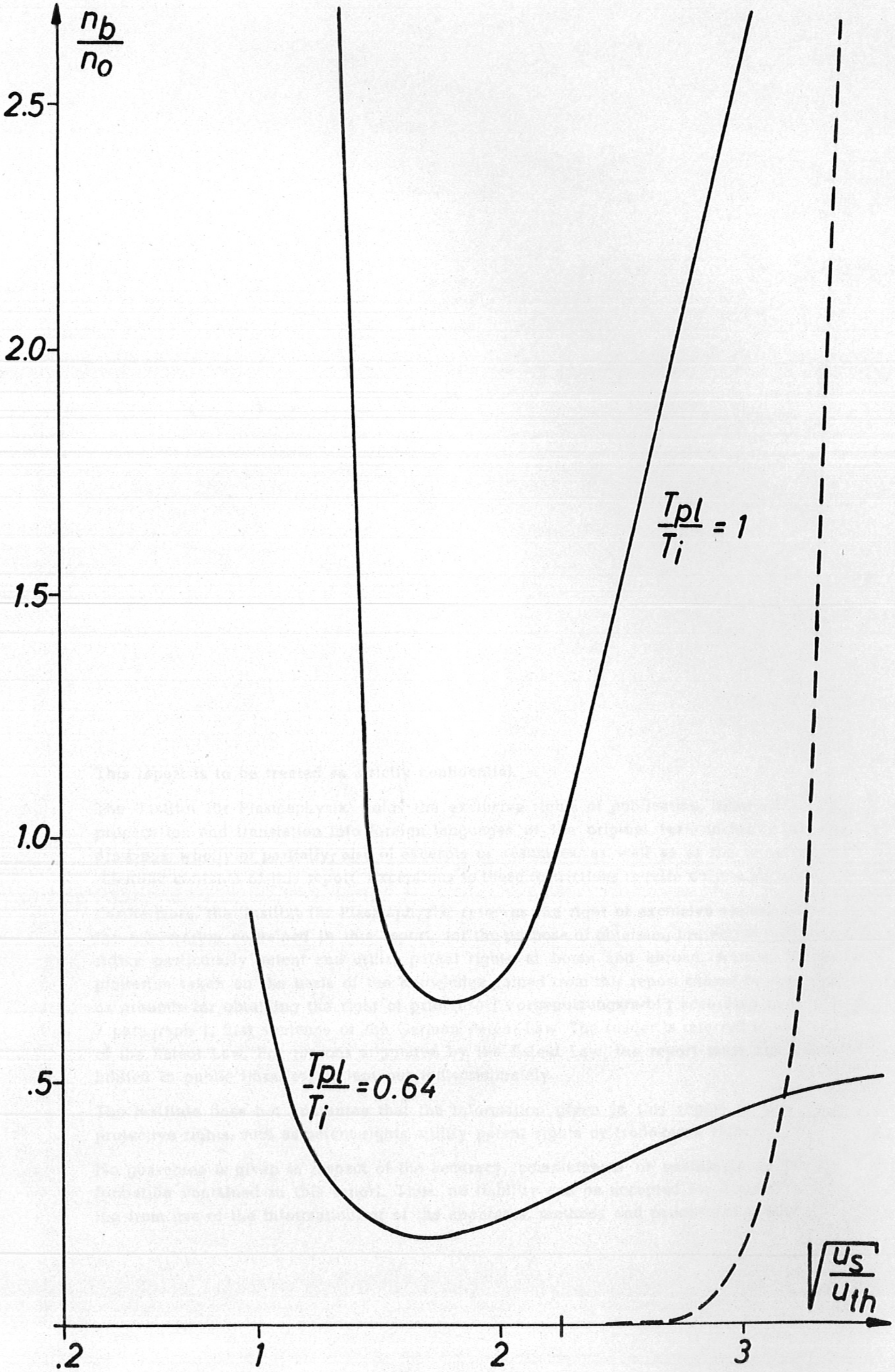
$\frac{n_b}{n_o}$
2.5
2.0
1.5
1.0
.5
$\frac{T_{pl}}{T_i} = 1$
$\frac{T_{pl}}{T_i} = 0.64$
$\sqrt{\frac{u_s}{u_{th}}}$
.2
1
2
3

Fig.7