On the Potassium Confinement in the Garching Octopole W V

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Abstract

This report is written in connection with a paper given at the 3rd European Conference, Utrecht /1/; the text of which is reproduced here as part I. Besides more detailed information on the experimental conditions (part II of this report), in part III the loss fluxes and the corresponding confinement times of a potassium plasma due to the presence of the ring supports of the Octopole are estimated.

Primary losses corresponding to a confinement time τ_{s1} are by direct loss of the gyrating ions at the surfaces of the supports. The calculated confinement time due to those primary losses is independent of the density. Secondary losses corresponding to a time τ_{s2} can be caused by an azimuthal density gradient. Depending on its direction, secondary losses are either towards the outer walls or towards the rings, the direction of the magnetic field being given. In the simple model treated here, instead of the density gradient only the ratio n_1/n_o enters where n_1 is the density measured at an azimuth where supports are located and n_o is the corresponding density at other azimuthal positions.

With the use of the experimental data as obtained until now, an experimental confinement time $\tau = 0.2$ s as well as loss times $\tau_{s1} = 0.5$ to 0.8s and $\tau_{s2} = 0.6$ to 0.04 s are found for a potassium plasma, in the purely meridional magnetic field of the Octopole W V. Considering the sheath effect on the primary loss flux to the supports the time τ_{s1} is to be reduced by a factor between 2 and 3.

The confinement properties of the Octopole in this experiment appear to be governed by the presence of the ring supports,

either predominantly by primary losses, if one assumes a strong sheath effect on the corresponding particle flux,

or predominantly by secondary losses, if one is allowed to neglect the sheath enhancement of the primary losses, or by any combination of primary and secondary losses.

The gap between the different interpretations is within about a factor of 3 in the loss fluxes. In the first case an electric field of the order of a few mV/cm is required to balance the observed azimuthal density gradient. In the conclusions of part I a further approach to measure the relative amount of secondary losses is proposed.

P A R T I

Introduction

Previous experiments with a Cs plasma and a moderate magnetic field in the Octopole W V /1-3/ yielded an appreciable increase in peak density when an azimuthal magnetic field (typically of 65 G) was superimposed on the purely meriodional multipole configuration. This feature was discussed /2, 3/ as part of a qualitative loss model, especially in the case of a collisionless plasma with a non-Maxwellian ion distribution and large ion Larmor radii. Using a K plasma and furthermore enlarging the magnetic field as compared to the above mentioned Cs experiments, within about 20% we find the same peak densities in both cases, with and without the azimuthal magnetic field applied /3/. This leads to the conclusion that large Larmor radii effects as regarded dominant in the case of a Cs plasma at low magnetic fields are no longer of such relevance /3/.

Therefore, in the present paper, some details of the confinement of a potassium plasma in the Octopole are studied. Effects of the supports of the current rings inside the vacuum tank are considered to be of importance. Consequently, it appears useful to investigate the purely meridional magnetic field configuration because of its simpler structure without translational transform or shear.

Experiments and Discussion

The apparatus as well as the plasma source and the diagnostics are described elsewhere /2, 3/. Fig. 1 shows the magnetic field plot. In the present investigation we use higher magnetic fields than those stated in the references. At the midplane of the device about 12 Larmor radii ϱ_i of a

0.2 eV potassium ion are between the boundary field line of a flute-stable confinement, ψ_c, and the main separatrix. The maximum magnetic field of the main separatrix is B_o=5.2 kG. The experiments are done in the stationary state. Axial and radial density profiles are shown in fig. 2. Three single Langmuir probes are used and cross-calibrated during several runs. The data are normalized to an ion input flux of $\phi = 3.4\cdot 10^{15} s^{-1}$. The profiles are taken at different azimuthal positions φ=60, 120 and 180° with respect to the plasma source. At φ=120° they reveal somewhat lower peak densities than at the other positions. The profiles are rather flat-topped and show close to the minor separatrices a moderate dip. As compared to the profiles of a Cs plasma at lower magnetic field we find steeper gradients which tend to vanish outside the critical field line ψ_c. There

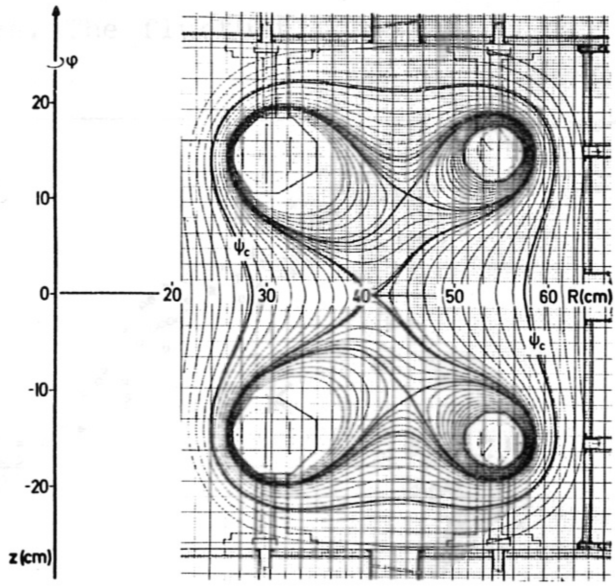

Fig. 1 Magnetic field plot

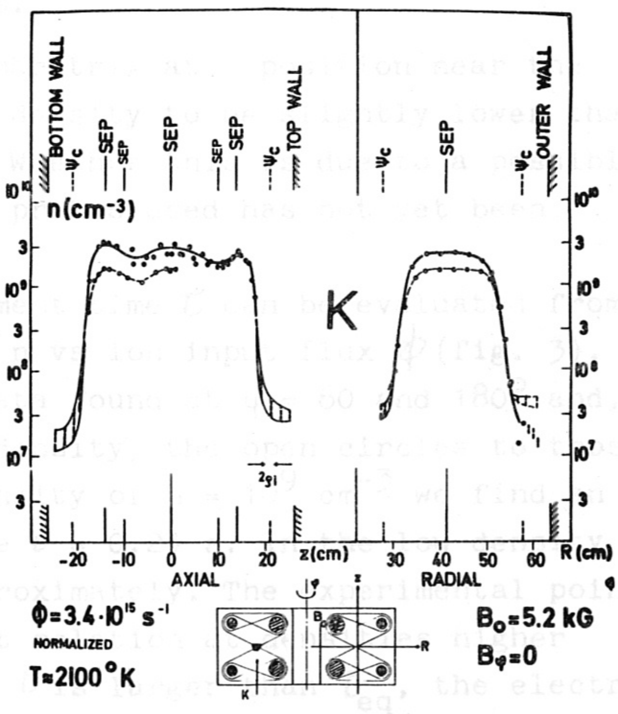

Fig. 2 AXIAL AND RADIAL DENSITY PROFILES

PROBES AT φ = 60° 180° 120°

fluctuations are observed the amplitude of which is indicated by the dashed vertical lines. The fluctuations seem to be present inside of ψ_c at a distance comparable to $2\varrho_i$, the Larmor diameter of a 0.2 eV potassium ion. This feature as well as further details of the fluctuations remain to be studied in the future; especially their relevance with respect to plasma losses.

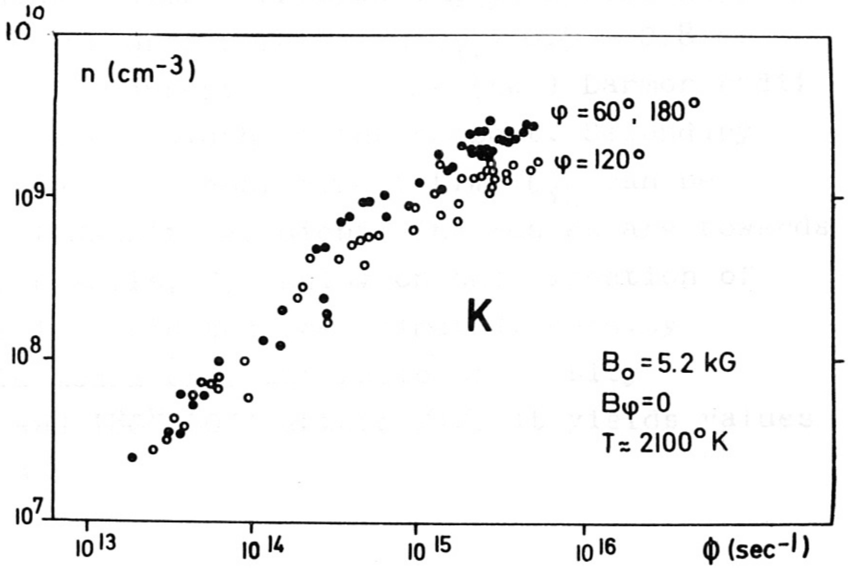

Fig. 3 DENSITY VS ION INPUT FLUX

Measuring at the main separatrix at a position near the upper outer ring we find the density to be slightly lower than at the center of the device. Whether this is due to a possible discrepancy of the different probes used has not yet been proved.

The experimental confinement time τ can be evaluated from the relation of peak density n vs ion input flux Φ (fig. 3). The dots correspond to the data found at φ = 60 and 180° and, at generally slightly lower density, the open circles to those at φ = 120°. At a typical density of n = 10^9 cm^{-3} we find an experimental confinement time τ = 0.24 s. In the low density region $n \sim \Phi$ is obtained approximately. The experimental points seem to rise slower than that relation at densities higher than $n \approx 0.7 \cdot 10^9$ cm^{-3}. There τ is larger than τ_{eq}, the electron-ion equipartition time; τ tends to decrease slightly with increasing density.

Diffusion mechanisms according to FICK's law with tha BOHM or the resistive diffusion coefficient yield confinement times much too low (7 ms) or too high (45 s, at $n = 10^9$ cm^{-3}), respectively. With the use of the profiles measured close to the rings the confinement time corresponding to direct loss of particles at the ring supports results in $\tau_{s1} = 0.5 - 0.8$ s. The lower (higher) value corresponds to one (two) Larmor radii added on either side to the width of the support. Secondary support losses according to a confinement time τ_{s2} can be caused by an azimuthal density gradient. The losses are towards the rings or the outer walls, depending on the direction of the meridional magnetic field and the azimuthal density gradient. In a simple model only the ratio of density measured at $\varphi = 120$ and $180^o (60^o)$ enters /4/. It yields values of $\tau_{s2} = 0.6$ to 0.04 s.

Conclusion

The calculated confinement time τ_{s1} due to direct loss at the supports is found, on the average, higher by about a factor of three than the observed confinement time. From the observation of reduced density at the azimuth where the supports are situated we conclude that support losses of the secondary type should be present. Up to now, however, no definite experimental value seems to have been obtained. Measuring the flux of particles towards the outer walls at positions close to the azimuth of the supports and also reversing the polarity of the magnetic field should give more information about those additional particle losses. Far beyond the limits of consideration are losses according to BOHM or resistive diffusion, as stated previously.

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PART II Apparatus and operating conditions

The calculated /2/ Octopole magnetic field is shown in Fig. 1a. It consists of a vertical quadrupole configuration with a major separatrix encircling the four internal conductors. Close to the inner rings the maximum magnetic field of the major separatris is $B_o = 5.2$ kG.

Nested inside the two loops of the major separatrix one more horizontal quadrupole is situated. The stagnation points of the two minor separatrices are at a vertical distance of 21 cm. They are shifted radially outward by about 3.5 cm from the stagnation point of the major separatrix which is at a radial distance of 41.4 cm off the axis of rotational symmetry. The boundary field line, ψ_c, of a flute-stable confinement is well inside the vacuum tank.

Each of the four internal rings is suspended by three supports. Two small supports of 2 x 20 mm cross section are at $\varphi = \pm 120^o$; one having dimensions of 7 x 28 mm is at $\varphi = 0$. There current and cooling water are supplied. The long sides of the ring supports are parallel to the magnetic field.

The pulsed D.C. magnetic field is switched on for 1.5 s, at intervals of about 1 1/2 minutes. This duty cycle is determined by the efficiency of the water cooling of the internal conductors as well as by the time necessary to record the data and to make the necessary changes (e.g. to shift a probe) for the next pulse.

In order to avoid effects of drifting generator voltages on the field configuration only one generator (300 V D.C.) is used. It produces the magnetic field by appropriate currents in the four internal rings and the outer reverse windings.

This is done in a circuit as shown in Fig. 1b. With the aid of an additional resistor R = 37 mΩ the voltage in the two branches of the circuit are matched. Some data of the different circuit elements indicated in Fig. 1b are listed in Table I.

Table I Octopole circuit data

	inner ring	outer ring	reverse windings
radius r (m)	0.30	0.546	0.27 - 0.6 0.67
windings n	163	85	44 32
resistance R(Ω)	0.47	0.41	0.033
inductance L(Hy)	0.05	0.025	
time constant (s)	0.11	0.06	
current I (kA)	0.435	0.32	0.87
nI (kA)	71	27.3	
α	0.43	0.45	0.44

In the last row of Table I a dimensionless quantity α is given which represents the ratio of magnetic field strength actually produced to that as reported in Ref. /2/. As shown in Table I, the values of α obtained from the currents of the inner and outer rings differ from the average by $\pm$ 2 %, resp. Consequently the distances between the currents and typical points in the field pattern (e.g. the stagnation points) may deviate by about the same amounts from the distances as shown in the field line pattern. Since typically those distances are of the order of 10 cm, a shift of 0.2 cm is regarded negligable. This shift is comparable to the Larmor radius of a 0.2 eV potassium ion in the average Octopole magnetic field ($\bar{B} \approx 1.5$ kG) and equal to the length of the tips of the Langmuir probes which are used as diagnostic tool.

The potassium plasma is produced by contact ionization at the azimuth $\varphi = 0$ near the stagnation point of the major separatrix. The emitter is made from 2 mm diameter tantalum wire wound to a conical spiral of about 2 cm diameter and 2.5 cm heigth. The tip of the cone points downward towards the oven, which produces the potassium vapor beam. The current leads to the spiral are insulated. The D.C. heating is switched off during the times when the magnetic fields are applied. Then the spiral acts as a floating emitter with time dependant temperature.

At constant heating currents the temperature of the spiral was measured using a two-color pyrometer which had been checked with a calibrated tungsten filament lamp. The decrease of temperature after switching off the heating current was calculated. At the time when the experimental data are evaluated this results in a value of $T = 2100^{\circ}K$, with an estimated error of about 5 %.

Single Langmuir probes (2 mm in length and 0.5 mm in diameter) are used as diagnostic tool. The probe signals are evaluated at about 0.7 s after switching on the magnetic fields. At this time the magnetic fields have reached their final values (c.f. Table I) and the plasma has attained a stationary state. This is inferred from the practically time independent behavior of the observed floating potential.

Probe characteristics are taken at points of special interest, e.g. at the maxima of the profiles. The characteristics yield a factor h, by which the probe signal obtained at a probe voltage of - 9 V (with respect to the grounded vacuum tank) is higher than the probe reading extrapolated from the characteristic at the plasma potential. The latter is taken to be at + 0.8 V with respect to the observed floating potential. The value of h as obtained from the characteristic of a particular probe during each of the different experimental runs is used in those other measurements (e.g. the profiles or the relation of density on the ion input flux) where no complete probe characteristics are taken. A systematic influence of the azimuthal position on the factor h might be inferred from the observations, as shown in Table II. At the azimuth $\varphi = 120^{o}$ where the ring supports are situated the quantity h appears to the higher by about 30 % than at the other azimuthal positions investigated.

Table II

Evaluation of probe characteristics, taken at major separatrix at different azimuthal positions, at the center of the device or radially outwards of the upper outer ring. Ring supports are at $\varphi = 120^{o}$.

probe	azimuth φ (°)	position	ion input flux Φ (s^{-1}) x 10^{15}	density $n(cm^{-3})$ x 10^{9}	correction factor h
E 1	60	center	3.6	2.6	1.5
e 2	60	ring	2.1	1.2	1.4
E 2	120	center	3.4	1.3	1.8
E 1	120	center	2.7	1.2	1.9
e 3	120	ring	2.3	1.0	1.6
E 3	180	center	4.2	2.6	1.5
E 3	180	center	2.6	2.7	1.1
E 2	180	center	2.5	2.0	1.4
e 8	180	ring	2.3	1.1	1.3

From the probe readings U (either the extrapolated values of the characteristics, or the signals obtained at a probe voltage of - 9 V with respect to the grounded vacuum tank and reduced by the mentioned factor h) the ion density n is calculated according to the relation $n(cm^{-3}) = 3.8 \times 10^{7}\ U\ (mV)$. A probe resistor of 0.1 MΩ is used in parallel to the 1 MΩ input resistance of the oscilloscope. The probe dimensions are as stated above and the ion velocity is taken to be $v_i = 0.9 \times 10^{5}$ cm/s (potassium, T = 2000°K). An empirical correction factor 2.5 is applied in the above formula which is discussed in Ref. /3/.

The density profiles (Fig. 2) and the relation of density versus the ion input flux (Fig. 3) are discussed in part I. In addition Fig. 2b shows the radial density profiles as obtained near the upper outer ring. The data of several runs have been normalized to an ion input flux of $\phi = 3.4 \times 10^{15}$ (s^{-1}). As compared to the maxima of the density profiles of Fig. 2 the profiles obtained close to the upper outer ring show less pronounced dependance on the azimuthal positions, and as a general feature, a reduced density. The numerical comparison of peak densities is given in Table III.

Table III Peak densities obtained at different positions.

ion input flux	$\phi(s^{-1})$:	$3x10^{13}$	10^{14}	$3x10^{14}$	10^{15}	$3.4x10^{15}$
probe	azimuth			peak density (cm^{-3})		
center	60, 180	$3.3x10^{7}$	$1.2x10^{8}$	$4.2x10^{8}$	$1.2x10^{9}$	$2.1-3.4x10^{9}$
center	120	3.2	1.0	3.0	0.8	1.2-1.8
ring	60, 180	1.3	0.5	1.7	0.6	1.6-1.9
ring	120	1.0	0.3	1.0	0.4	1.3-1.6

The spread of the peak densities listed in the last column of Table III shows the relative agreement between the different probes used. Part of the reduction of peak densities obtained at an azimuthal position of $\varphi = 120^{\circ}$ is due to the apparent enhancement of the reduction factor h (see Table II) which is used in connection with the probe measurements.

Part III Support Losses

Direct loss of the gyrating ions at the surfaces of the supports will be called primary support loss. It is correlated with a confinement time τ_{s1}. If at first we neglect effects of the sheath formed close to the supports the loss flux to the supports is

$$\phi_s = 2 \; \frac{1}{4} v_i \; \sum_k \int n(z) \left(b_k + 2 \xi \varrho_i(z) \right) dz$$

Here $\frac{1}{4}$ v_i = 0.25 x 10^5 cm/s is the average directed velocity of a 0.2 eV potassium ion, n(z) is the vertical density profile. Contributions of the different (k) supports are summed. The material width of a support is b_k which is taken to be enlarged on both sides by ξ = 1 to 2 Larmor radii ϱ_i .

Since particles are streaming both in parallel and anti-parallel direction with respect to the magnetic field, a factor of 2 appears in the above relation of the total loss flux.

In the z-direction the magnetic field varies vertically along the supports of the inner (outer) rings from 4.5 to 2.5 kG (2.7 to 1.1 kG), resp. The higher values are at the ring surfaces and the lower ones at ψ_c, the critical field line. The Larmor radius of a 0.2 eV potassium ion is ϱ_i = 0.4/B (cm), if the magnetic field is taken in kG.

The integration along the vertical direction is done numerically. At vertical intervals of Δ = 0.27 cm) the effective width b_k + $2\xi\varrho_i$ of the three supports of one ring yields a total of 1.1 + $6\xi\varrho_i$ (cm) which is to be weighted by the vertical density profile.

Thus

$$\phi_s = 2 \; 2 \; \frac{1}{4} v_i \; n_2 \Delta \sum_\lambda \frac{n_\lambda}{n_2} \left(1.1 + 6 \xi \varrho_{i\lambda} \right)$$

where the sum over λ covers both the inner and the outer ring and a further factor of 2 takes into account the second pair of rings. The peak density n_r is as measured close to the major separatrix whereas a relative density profile n_λ/n_r is used in the computation of the sum. Then the latter results in $\Sigma = \sum_\lambda n_\lambda/n_r \, (1.1 + 6\,\xi\,\varrho_{i\lambda})$ = 18.2 (27.1) cm for $\xi = 1$ (2) Larmor radii added on either side of each of the supports. The confinement time τ_{s1} is obtained from the balance equation $\phi_s \tau_{s1} = \int n\,dV = n_c V$ where $V \simeq 2 \times 10^5\ cm^{-3}$ is an effective confinement volume and n_c is the peak density as measured at the center of the device. Combining the values given above yields

$$\tau_{s1} = \frac{1}{v_i} \frac{V}{\Delta} \frac{1}{\Sigma} \frac{n_c}{n_r} = 0.5 \text{ to } 0.8 \text{ s}$$

where a typical ratio $n_c/n_r \simeq 2$ of peak densities n_c and n_r as measured at the center and close to the ring, resp., is used (see Table III).

Considering the sheath effect /4/ on the loss flux ϕ_s, the calculated time τ_{s1} should be reduced by a factor between about 2 and 3.

Secondary support losses corresponding to a confinement time τ_{s2} can be caused by an azimuthal density gradient. Dependant on the direction of the azimuthal density gradient those secondary particle fluxes are transverse to the meridional magnetic field, and thus directed either towards the outer walls or towards the rings.

This results from the relation of perpendicular velocity

$$v_\perp = \frac{\vec{B}}{B^2} \times \left(-\vec{E} + \frac{\nabla p_i}{en} \right)$$

if, as a rough estimate, the electric field $\vec{E}$ is neglected. Assuming further a constant ion temperature T and linearizing the density gradient yields $v_\perp = \frac{1}{B} \frac{kT}{e} \frac{\nabla_\varphi n}{n} \approx \frac{1}{B} \frac{kT}{e} \frac{1}{\Lambda} \frac{n_o - n_1}{n_o}$ where Λ is an azimuthal scale length along which the density is reduced from n_o to n_1. The corresponding loss flux $\phi_\perp = \int n v_\perp dF$

is independant of this scale length:

$$\Phi_\perp \approx n_0 v_\perp L \Lambda = \frac{1}{\bar{B}} \frac{kT}{e} (n_0 - n_1) L$$

where L = 1.5 m is the length of a typical field line (# 9 in Ref. /2/, localized between the major separatrix and ψ_c) along which there is an average magnetic field of $\bar{B}$ = 1.6 kG = 0.16 Vs/m^2. If in this estimate the density n_0 is taken to be that as measured at φ= 60 or 180° and n_1 the density as obtained at the azimuth φ= 120° where the supports are located, V' = $\frac{1}{6}$ V = $\frac{1}{6}$ $\cdot$0.2 m^3 is to be used in order to obtain the confinement time corresponding to those secondary support losses of a plasma with thermal energy of kT/e = 0.2 V.

$$\tau_{s2} \simeq \frac{n_0 V}{\Phi_\perp 6} = \bar{B} \frac{1}{kT/e} \frac{1}{L} \frac{V}{6} \frac{n_0}{n_0 - n_1}$$

$$\tau_{s2} = \frac{0.018}{1 - n_1/n_0} \quad (s)$$

As given in Table III, in the present experiment on the Octopole, values of n_1/n_0 = 0.9$_7$ to 0.54 have been obtained from which values of τ_{s2} = 0.6 to 0.04 s result.

The rough model as treated above can be refined by better weighting of the contributions, both with respect to the direction of losses (towards the rings or towards the outer walls), and the dependance of the perpendicular velocity on the magnetic field. The loss flux due to secondary support losses is

$$\Phi_\perp = \int n v_\perp df = \frac{kT}{e} \int \frac{dl}{B} \nabla_\varphi n \, r \, d\varphi$$

Here we use the approximation of the perpendicular velocity as above and assume an orthogonal system of coordinates where the surface element is df = r dφ dl; dl is the line element of the field lines. Since $\nabla_\varphi n = \frac{1}{r}\frac{\partial n}{\partial \varphi}$ this results in

$$\Phi_\perp \approx \frac{kT}{e} \oint \frac{dl}{B} \int dn = \frac{kT}{e} (n_0 - n_1) \oint \frac{dl}{B}$$

In order to obtain the confinement time $\tau_{s2} = \frac{n_o V'}{\Phi_\perp}$ the fraction V' of the confinement volume V = 0.2 m^3 is to be used which is enclosed between the azimuthal positions where the densities n_o and n_1 are obtained. This is done for φ = 60 to 180°, in order to account also for the loss fluxes directed towards the rings; V' = V/3. As typical field lines encircling the inner (outer) rings we choose # 16 (26) from Ref. /2/, in addition to # 9. For the magnetic fields as used in this experiment (α = 0.44) and the field lines stated the sum $\Sigma = \oint_{\#9} dl/B + 2\left(\oint_{\#16} dl/B + \oint_{\#26} dl/B\right) =$ = 288 cm/kG = 28.8 m^3/Vs from which the confinement time $\tau_{s2} = \frac{0.012}{1 - n_1/n_o}$ (s) is obtained, in sufficient agreement with the value used in part I.

Support losses of the secondary type can be absent if an azimuthal electric field balances the azimuthal pressure gradient.

As an order-of-magnitude estimate of the balancing electric field the azimuthal decay length of the density distribution is assumed to be about the distance $R_o \approx$ 40 cm of the observation positions φ = 60, 120, 180° where the density values n_o and n_1 are evaluated. Using kT/e = 0.2 V a value of $E = \frac{\nabla p_i}{en} \approx \frac{kT}{e}\frac{1}{R_o}$ = 5 mV/cm is obtained, which value is thought to be close to a lower limit of the electric field.

Conclusion

From the observed confinement time in comparison with calculated times of primary and secondary support losses two different interpretations as well as any combination of them appear possible, within a factor of about 3 in the loss fluxes:

a) If a strong sheath effect enhances the primary support losses by a factor of about 2 to 3 as compared to those calculated without the sheath effect, an agreement is obtained between the reduced primary support loss time and the experimental confinement time. Then the observed azimuthal density dependence should be balanced by an electric field of the order of at least a few mV/cm.

b) If it is allowed to neglect the sheath effect on the primary loss flux to the supports, then secondary support losses higher than the primary ones should be present. They are consistent with those values obtained in a simple model if one neglects an azimuthal electric field.

As stated in the conclusion of part I more information about secondary losses might be obtained if one measures the flux of particles e.g. towards the outer walls at an azimuthal position close to the supports and uses also a reversed magnetic field.

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Acknowledgement

The author wishes to express his thanks to Prof. B. Lehnert for discussions concerning particle fluxes, during which ref. /4/ had been brought to his attention once more.

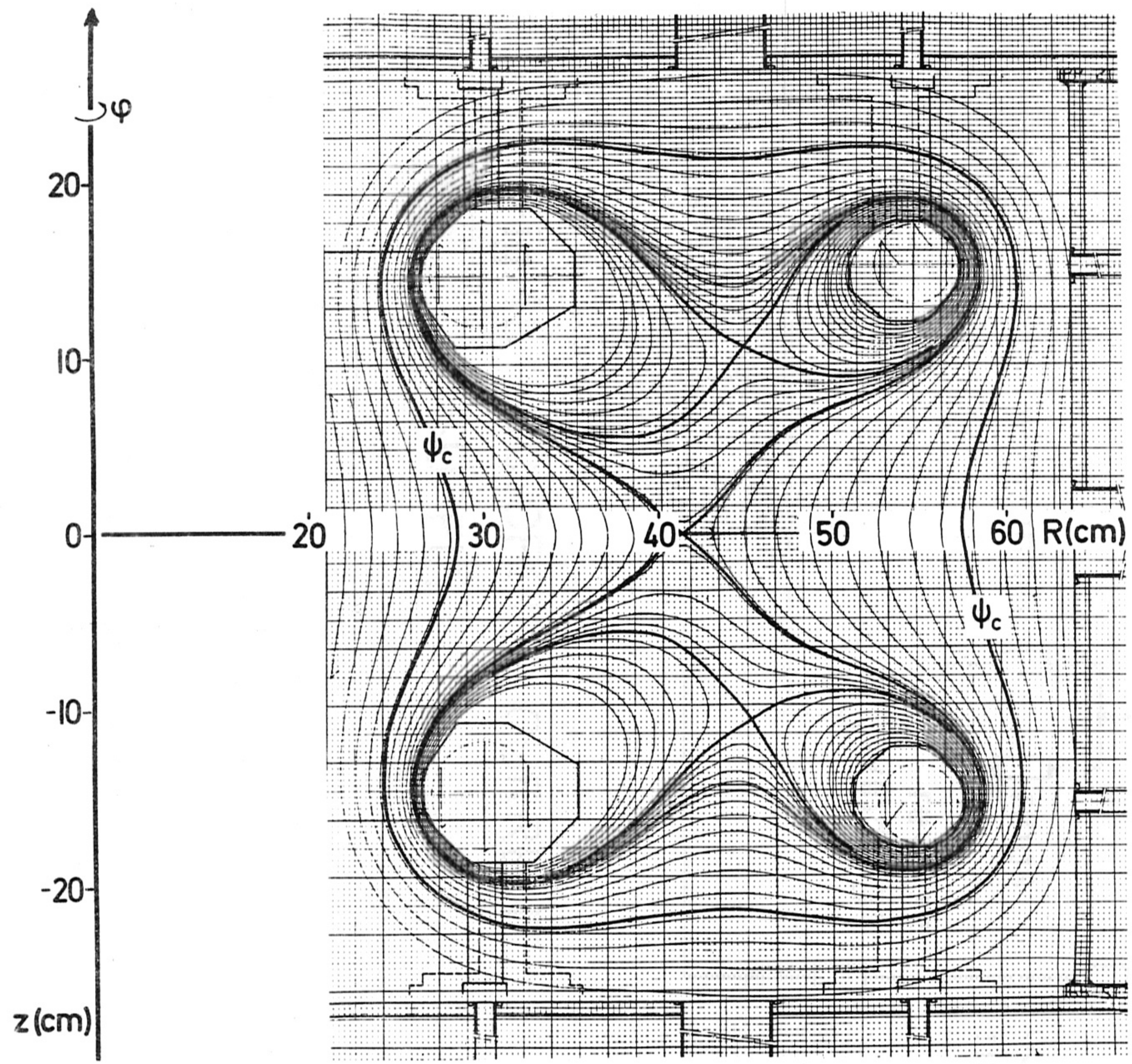

Fig. 1a

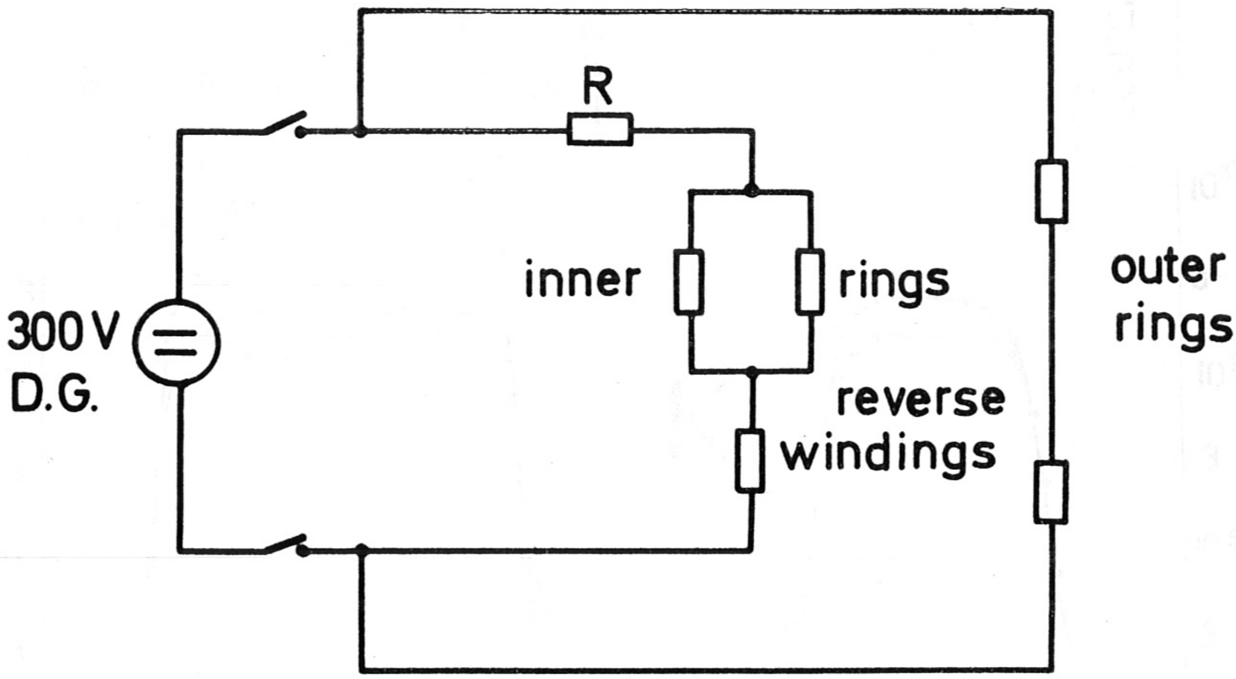

Fig. 1b OCTOPOLE CURRENT SUPPLY

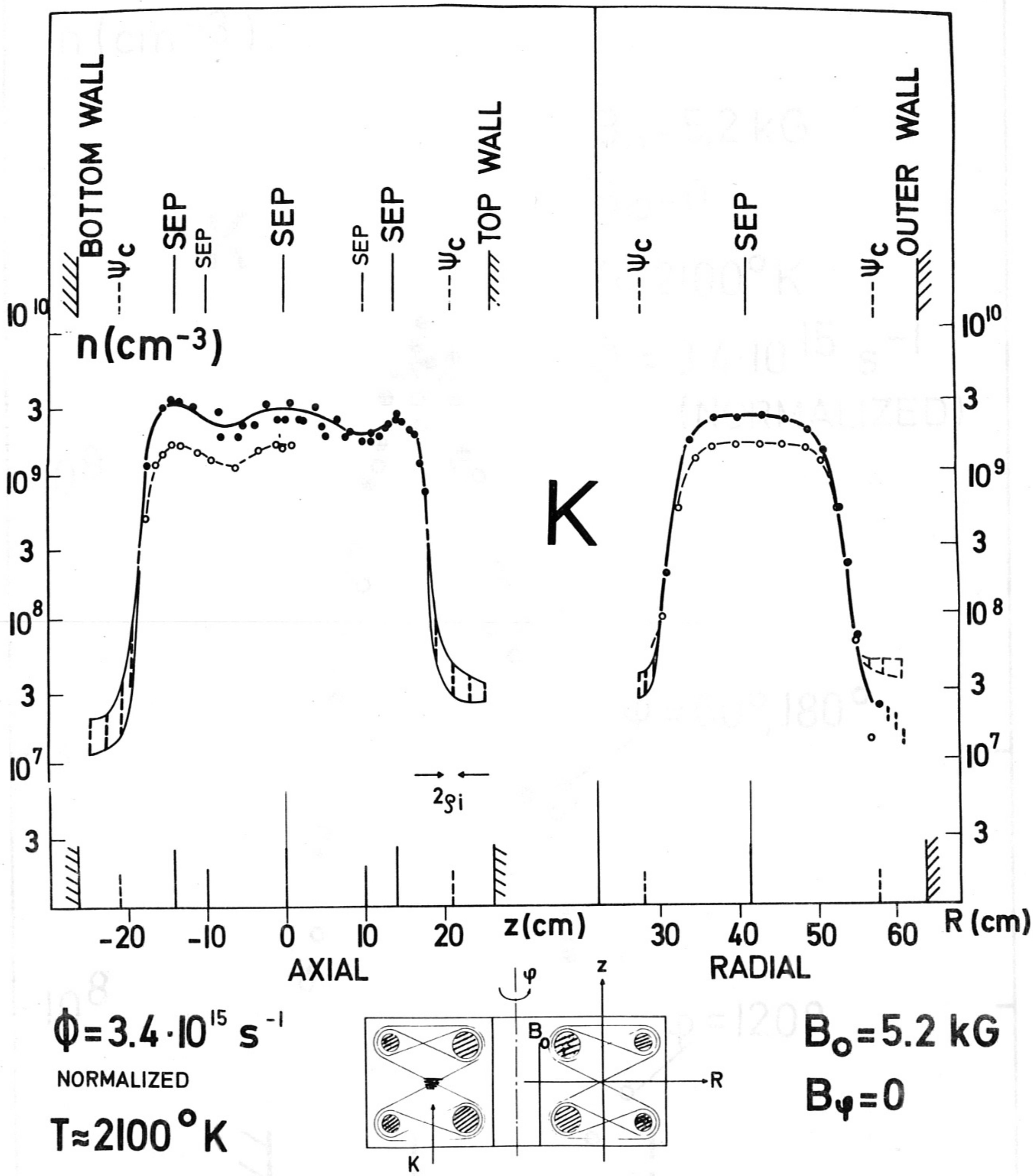

Fig. 2 AXIAL AND RADIAL DENSITY PROFILES

PROBES AT $\varphi =$ 60° 180° 120°

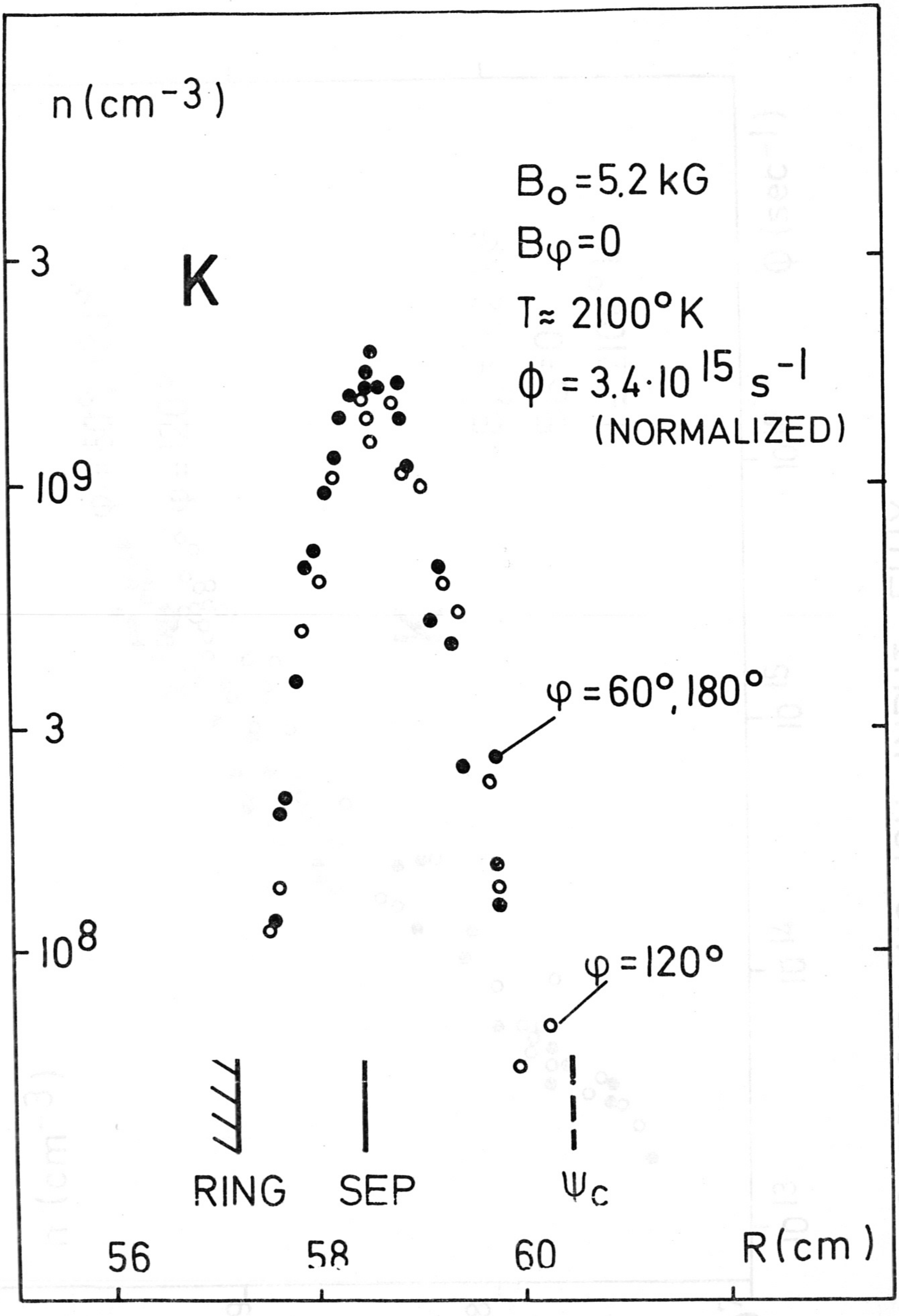

Fig. 2b RADIAL DENSITY PROFILE NEAR OUTER RING

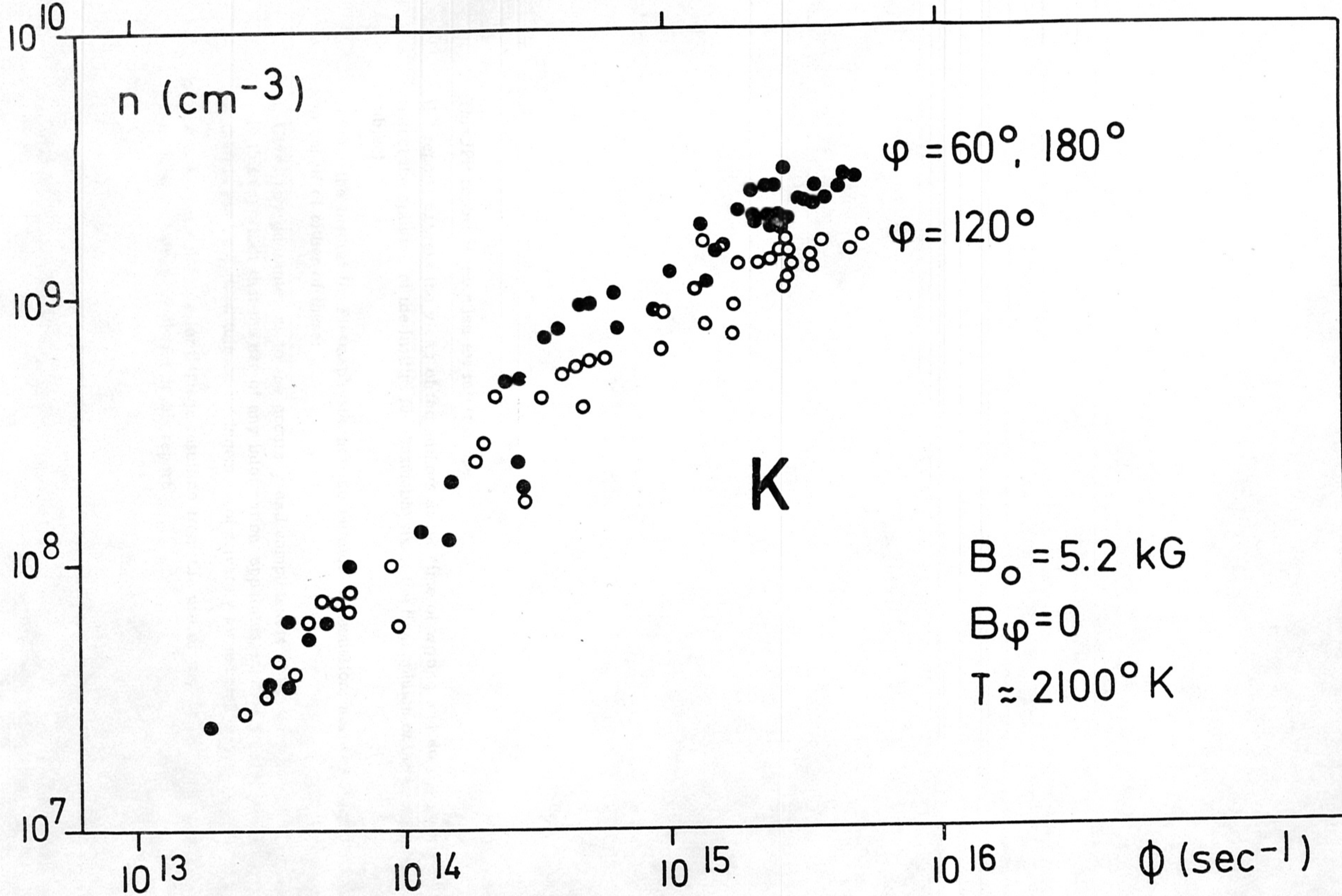

Fig. 3 DENSITY VS ION INPUT FLUX