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High Temperature Plasma with a Cold Gas Blanket in a Toroidal Magnetic Field

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Abstract

The maximum attainable plasma temperature in a linear high current high density arc with a longitudinal magnetic field is limited by the end losses. In a plasma torus, end losses do not occur. There is, however, the question what influence the curvature has on the plasma, i.e. whether an arc in a toroidal magnetic field can burn in a stable manner in the centre of the vessel or whether it is displaced to the wall, and how large the energy losses and axial temperature are compared with those of an arc in a linear magnetic field. To solve this problem using the classical heat conduction equations for ions and electrons, the temperature profile resulting from ohmic heating was calculated as a function of time. Since the thermal conductivity parallel to the magnetic field is high, the temperature in the hot regions is constant on the magnetic surfaces. The magnetic surfaces are formed by superposition of the magnetic field produced by the discharge current on the high longitudinal field. The rotational transform thus obtained ensures that the plasma is in equilibrium. The position of the plasma is given by the wall isotherms.

As a preliminary study of the conditions in the whole torus, two independent experiments with torus sectors for investigating discharges in hydrogen and helium were conducted. The experimental data are as follows: torus diameter 1 m (30^{o} sector) and 0.7 m (180^{o} sector), plasma diameter approx. 3 cm, plasma density 10^{15} - 10^{16} cm^{-3}, discharge current 3 kA, discharge time 1 msec and 20 msec respectively, external magnetic field 50 kG and 25 kG respectively.

The results of the experiment are as follows:

a) The hot regions of the plasma (axial temperatures up to about 100 000 ^{o}K) are not forced to the outer wall, as widely feared, but rather tend to be slightly displaced to the inner wall.

b) Using streak pictures in the light of HeII (λ = 4686 Å) it is found that, with a suitable choice of parameters, the arc is stable.

c) The losses in the toroidal discharge are not much higher than in the linear case, as measurements of the longitudinal electric field strength and axial temperature show.

The results of the calculations and the two experiments arouse hopes of obtaining a stationary high temperature plasma free of MHD instabilities by neutral gas confinement in a closed torus with a superposed magnetic field.

1. Introduction

This paper deals with the properties of a plasma in toroidal geometry that is separated from the wall of the vessel by neutral gas. In the theoretical model of a stellarator without anomalous diffusion the energy transport to the wall is governed by classical diffusion so that the density vanishes there, while the temperature should remain everywhere as constant as possible.

This investigation, on the other hand, is concerned with a high density discharge ($n = 10^{15} - 10^{16}$ cm^{-3}) in which a temperature profile occurs as a result of thermal conduction and a neutral gas blanket forms at the boundary in keeping with the local thermal equilibrium. The plasma is produced by ohmic heating in a high external magnetic field. The mean free-path for charge-exchange collisions is so small that no neutral particles are able to diffuse into the fully ionized plasma core.

Such discharges have been investigated hitherto only in uniform, linear magnetic fields [1,2] and so extension to curved magnetic fields raises the following questions: How is the temperature profile influenced by the curvature of the magnetic field and how is the plasma column kept in equilibrium? The theoretical investigations are concerned with a closed toroidal configuration, while the experiments were conducted on torus sectors.

2. Description of experiments

a) EIERUHR K

The experimental setup is shown in Fig. 1. The discharge configuration is a development of the linear EIERUHR device[2]. The dimensions of the original experiment were essentially retained to allow comparison between linear and curved geometries.

The discharge vessel consists of a glass tube with an inner diameter of 5.4 cm. It is bent for a length of 60 cm to form a torus sector with a radius of curvature of 1 m. The longitudinal magnetic field (B_o to 50 kG) is produced by a pancake coil in a transparent cast, thus allowing the plasma column to be observed along its entire length. The plasma current flows from ring electrodes through guide funnels, as in the original EIERUHR device (for the most important data of the EIERUHR K device, see Table I).

A streak camera and a spectrograph were used to observe the plasma in the centre of the discharge vessel in the direction of the torus radius and parallel to the torus axis. Streak pictures were taken in the light of the He II line $\lambda = 4686$ Å.

In addition, time resolved framing pictures were taken of the whole plasma channel in the light of the He I line $\lambda = 4471$ Å during the entire discharge time. In this way, it was possible to observe the position of the plasma, the shape of its cross section, and its stability.

b) AMBIPOL IV

The AMBIPOL IV experiment is shown in Fig. 2. The layout and dimensions are similar to those of AMBIPOL III [3]. The discharge consists of a semi-toroidal and a linear measuring section of equal length (1.10 m) with superposed longitudinal magnetic field B_o (up to 30 kG). For equal current (up to 3 kA) and equal neutral gas pressure (approx. 5 torr), it is thus possible to make a direct comparison of the conditions in the toroidal section with those in the linear section. For this purpose, one spectrograph was mounted at the centre of the toroidal section and another at the linear section, thus allowing the temperature profiles to be investigated. Potential probes designed as copper limiters are used to measure the longitudinal electric field in the toroidal and linear sections at the same current. This enables the energy balance in the two sections to be compared. Table I lists the most important parameters of the discharge.

The two end electrodes are designed to serve as both anode and cathode, and so the direction of the discharge current can be reversed. The continuously streaming neutral gas (H_2 + 10 % He) was always admitted at the cathode and extracted at the other end of the discharge. The windings denoted by "$B_\perp$" in Fig. 2 produce in addition to the longitudinal magnetic field B_o a transverse magnetic field $\vec{B}_\perp$ (up to 1 kG) parallel to the torus axis. This field can be used together with the main current J_o to shift the discharge channel in the transverse direction as a result of the $\vec{J}_o \times \vec{B}_\perp$ force.

3. Results

a) Calculation of the temperature profile

While the temperature in the linear case is constant on a certain radius r and the temperature maximum is at the centre, the energy balance equation for the toroidal case contains an additional heat flow in the azimuthal direction the divergence of which does not vanish owing to the curvature of the magnetic field and which can cause the isotherms to shift in the Z-direction (Fig. 3). The energy balance equations of a fully ionized plasma were numerically solved for the two temperatures T and T_i.

The two energy equations are:

$$\frac{3}{2}nk\frac{\partial T}{\partial t} + \operatorname{div}\vec{s} + \frac{3mnk}{M\tau}(T - T_i) = \sigma E^2 ; \tag{1}$$

$$\frac{3}{2}nk\frac{\partial T_i}{\partial t} + \operatorname{div}\vec{s}_i - \frac{3mnk}{M\tau}(T - T_i) = 0 ; \tag{2}$$

$$\vec{s} = -4.67\frac{nk^2Tc}{eB\omega\tau}\vec{\nabla}_\perp T - 2.3\frac{nk^2T\tau}{m}\vec{\nabla}_\parallel T + \frac{5}{2}\frac{nk^2Tc}{eB^2}\vec{\nabla}T\times\vec{B} ; \tag{3}$$

$$\vec{s}_i = -1.45\frac{nk^2T_ic}{eB\omega_i\tau_i}\vec{\nabla}_\perp T_i - 5.5\frac{nk^2T_i\tau_i}{M}\vec{\nabla}_\parallel T_i + \frac{5}{2}\frac{nk^2T_ic}{eB^2}\vec{\nabla}T_i\times\vec{B} ; \tag{4}$$

where

n = particle density, T = electron temperature, T_i = ion temperature, B = longitudinal magnetic field, m = electron mass, M = ion-mass, τ = electron-ion collision time, τ_i = ion collision time.

Numerical solution was made by a time difference method in which the temperature was fixed on the circumference of a circle with radius r_p = 2 cm. The calculations were made for a hydrogen plasma with torus diameter of 60 cm and an external magnetic field of 100 kG. The particle density n = 10^{15} cm^{-3} was assumed constant in both space and time. This entails only a small error in the solution for the temperature profile. This is because the relation between density and temperature gradient (Nernst effect[4]) causes the density to vary very little with the temperature ($n \sim T^{-1/4}$). The electric field, which is constant over the radius, was chosen so that the discharge current density rises in 5 x 10^{-4} sec to 1.6 kA cm^{-2}. Iteration commenced with a uniform temperature distribution of T = 10^4 °K. The temperature profile for this discharge at the time t = 2.7 x 10^{-4} sec is plotted in Fig. 4. The temperature rise is 20 % steeper at the inside wall of the torus ($\vartheta = 0$) than at the outside wall. This shift cannot be due to the $\vec{\nabla}T \times \vec{B}$ term in the energy equation since this term can only cause a shift in the Z direction. The heat flow parallel to the magnetic field, in turn, produces a symmetric temperature profile as a result of the thermal conductivity parallel to the field lines. A temperature balance parallel to the field lines is present because the self-magnetic field of the current is superposed on the longitudinal magnetic field so that magnetic surfaces are formed [4,5] . It is therefore assumed that it is thermal instabilities that are involved here, these being contained in eqs. (1) and (2). At the time t = 2.7 x 10^{-4} sec, the rise time of these instabilities is t_A = 5 x 10^{-5} sec, i.e. a factor of 10 faster than the current rise time. It is being checked whether these instabilities can be avoided by choosing a faster current rise time. In the steady state, the electric field is so small that the stabilizing effect of the thermal conductivity parallel to the magnetic field predominates. The step size was varied to check whether the results are independent of numerical instabilities.

b) Experimental results on temperature distribution

The drift pattern in a toroidal plasma in vacuo with a superposed, uniform magnetic field without rotational transform (i.e. the plasma is forced outward to the vessel wall (cf. [7])) suggests at first glance that in our case the temperature maximum should shift toward the outside wall of the torus. The experimental results for our plasmas with a neutral gas blanket show, however, much more favourable behaviour. From the first spectra recorded (cf. Fig. 5, He II $\lambda = 4686$ Å, He I $\lambda = 4713$ Å) it can be seen that the temperature maximum does not shift outward, but tends rather to be stationary and symmetric, and, in many cases, it is even a little closer (approx. 2 - 3 mm) to the inside wall of the torus.

Short-circuiting of the transverse electric fields at the copper nozzles of the electrodes cannot be the cause of the profile symmetry since the same results were obtained with insulated nozzles.

c) Comparison between linear and toroidal discharges

On comparing the axial temperatures in the linear and toroidal sections of AMBIPOL IV (approx. 70 000 °K) or those in the linear EIERUHR and EIERUHR K (approx. 100 000°K), it is found that the temperatures in the toroidal plasmas are not essentially lower.

The longitudinal electric field strengths in the two sections of AMBIPOL IV agree within the measuring accuracy. They are approx. 2.5 V/cm. The electric field in the EIERUHR K is approx. 10 V/cm, which agrees within the measuring accuracy with that measured in the linear EIERUHR.

It is found that the cross section of the plasma channel in EIERUHR K is a factor of 2 - 2.5 larger in area than the linear EIERUHR and that is not always circular. The shape of the cross section is governed mainly by the filling pressure. The ratio of the transverse dimensions of the plasma cross section is plotted in Fig. 6 as a function of the filling pressure.

d) Effect of a transverse magnetic field

The plasma AMBIPOL IV was subjected to an externally controllable transverse force by using additional windings to produce a transverse magnetic field $B_\perp$ which is parallel to the torus axis and which results in a Lorentz force in the torus plane perpendicular to the torus axis. From the two discharge spectra in Fig. 7, which were recorded for different polarities of the $\vec{J}_0 \times \vec{B}_\perp$ force, it can be seen that a transverse magnetic field of only 2 % of the main field is already sufficient to cause a distinct shift of the emission maximum of the He II line λ = 4686 Å and hence of the hot regions of the plasma. For B = 1 kG, the wall of the torus is destroyed by thermal stress. Whereas the destruction of the wall occurs in each case on that side at which the Lorentz force is directed, the shift of the emission maximum takes the opposite direction (Fig. 7). This suggests that the flow in the plasma (without $B_\perp$ as well) may be of the type found in investigations of the retrograde motion of arcs [8].

Any dependence of the longitudinal electric field strength in the toroidal section of the applied transverse field $B_\perp$ is within the present measuring accuracy. The temperature in the maximum apparently drops, however, when the transverse magnetic field is applied (500 G), as can be seen in Fig. 7.

e) Equilibrium of forces and flow in the plasma

Even without a transverse magnetic field, there must be flow in the toroidal plasma to maintain equilibrium. While the position of the plasma column in the TOKAMAK is determined by the repelling forces of the metal wall, the position of the column is governed here by the temperature profile resulting from the energy balance (eqs. (1), (2)) at the given boundary temperature and electric field strength. The temperature distribution together with the current distribution gives rise to a meridional magnetic field $\vec{B}_\vartheta$, which combines with the longitudinal field to form magnetic surfaces on which the pressure is constant when equilibrium is present. If it is assumed that the density, temperature and B_ϑ depend only on r, the equilibrium here corresponds exactly to the LEVITRON case, the only difference being that here the discharge channel takes the place of the internal conductor. Classical diffusion has been calculated in [9], where the inertia terms in the equation of motion have been neglected. The flow field of a toroidal discharge with temperature gradient was also calculated [5] in a similar manner to that in [9].

The result for the velocity $\vec{v}$ is:

$$v_\theta = \frac{2\pi}{\iota} R_0 \frac{d}{dr}\left(\frac{4\pi^2}{\iota^2} \frac{R_0}{r} \frac{c^2}{\sigma B^2} \frac{dp}{dr}\right) \sin\vartheta + O\left(\frac{r}{R_0}\right); \tag{3}$$

$$v_r = \frac{4\pi^2}{\iota^2} \frac{R_0}{r} \frac{c^2}{\sigma B^2} \frac{dp}{dr} \cos\vartheta - \frac{2\pi^2}{\iota^2} \frac{c^2}{\sigma B^2} \frac{dp}{dr} + O\left(\frac{r}{R_0}\right); \tag{4}$$

$$v_\vartheta = \frac{4\pi^2}{\iota^2}\,\frac{R_0}{r}\,\frac{c^2}{\sigma B^2}\,\frac{dp}{dr}\,\sin\vartheta + O\left(\frac{r}{R_0}\right); \qquad (5)$$

where θ denotes the direction of the longitudinal magnetic field and $\frac{2\pi}{\iota}$ the rotational transform (Fig. 3). In this velocity field, the longitudinal velocity v_θ is largest and diverges for $r \rightarrow 0$. At the zero $r = 0$, the solution for v_r and v_ϑ is not valid either because the values from eqs. (4) and (5) are not unique there. The flow pattern for the velocity field of eqs. (4) and (5) is plotted in Fig. 8, the second term in eq. (4) being neglected. The flow lines are circles with their centres on the axis $R = R_0$ that touch at the point $Z = 0$, $R = R_0$.

This velocity field involves the difficulty that there is permanent mass transport from the outside wall of the torus to the inside wall. It must therefore be assumed that a solution satisfying the boundary conditions is only obtained by taking the inertia terms into account. The energy transport caused by the flow (eqs. (4), (5)) is of the order of the thermal conductivity of the electrons, while the total energy loss is governed by the thermal conductivity of the ions. The contribution of the flow to the energy transport in eqs. (1) and (2) was therefore neglected in the calculation of the temperature profile.

It was attempted experimentally to measure the flow in the outer region ($T = 20\,000$ °K approx.) of the plasma channel. An estimate showed that the velocity there must be below 10^5 cm/sec. Velocity measurements in the hot region of the plasma are being prepared. The velocities here are expected to be high (velocity of sound).

f) Stability

In this type of discharge ($\beta \approx 10^{-3}$) magnetohydrodynamic instabilities cannot occur [10]. As a result of the steep temperature gradients, however, ion temperature driven drift instabilities are to be expected. These should lead to anomalous heat conduction losses, but these only become effective at higher temperatures than those attained experimentally so far [10]. A closed toroidal discharge should make it possible to investigate these anomalous losses at high temperatures (10^6 °K) by optical measurements of the temperature profile.

With the discharge parameters of EIERUHR K listed in Table I, no fluctuations in intensity could be observed in streak pictures taken in the light of the He II line $\lambda = 4686$ Å and framing pictures taken in the light of the He I line $\lambda = 4471$ Å, the camera being directed in each case in two mutually perpendicular directions. As an example, Fig. 9 shows a streak picture of the discharge taken in the direction parallel to the torus axis. (The dark strip in the centre of the picture is caused by an opaque strut inside the field coil).

The results of the calculations and the two experiments arouse hopes of obtaining a stationary high temperature plasma free of MHD instabilities by neutral gas confinement in a closed torus with a superposed magnetic field.

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	EIERUHR K	AMBIPOL IV
gas used	Helium	Hydrogen + 10 % Helium
filling pressure	1-6.5 torr	approx. 5 torr
discharge current	approx. 2 kA	up to 3 kA
magnetic field	up to 50 kG	up to 30 kG
plasma density	10^{16} cm^{-3}	approx. 3×10^{15} cm^{-3}
discharge time	up to 1 msec	20 msec
radius of curvature	1 m	35 cm
diameter of discharge vessel	5.4 cm	5.2 cm
plasma diameter	approx. 3.5 cm	approx. 3.5 cm
angle of sector	approx. 30°	180°

Table I

FIGURE CAPTIONS

Fig. 1	Schematic of EIERUHR K
Fig. 2	Schematic of AMBIPOL IV
Fig. 3	Coordinate system used
Fig. 4	Electron temperature profile at the discharge time $t = 0.28$ msec
Fig. 5	Side-on spectra of EIERUHR K and AMBIPOL IV (line of sight parallel to torus axis)
Fig. 6	Ratio of transverse dimensions of the plasma versus neutral gas pressure in EIERUHR K (d_v = dimension in the vertical direction (parallel to torus axis), d_h = dimension in the horizontal direction (parallel to torus radius))
Fig. 7	Influence of the transverse magnetic field on the side-on spectrum of AMBIPOL IV
Fig. 8	Flow pattern in torus assuming classical diffusion
Fig. 9	Streak picture of the discharge in EIERUHR K in the light of He II (4686)

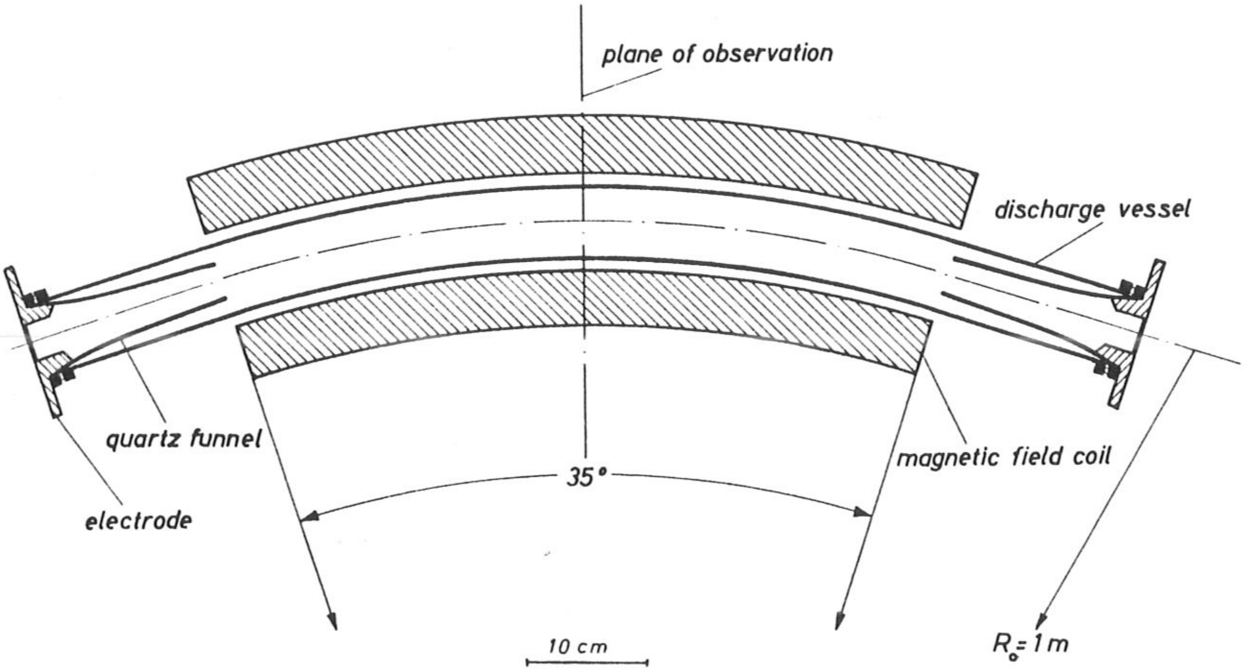


Fig. 1 Schematic of EIERUHR K

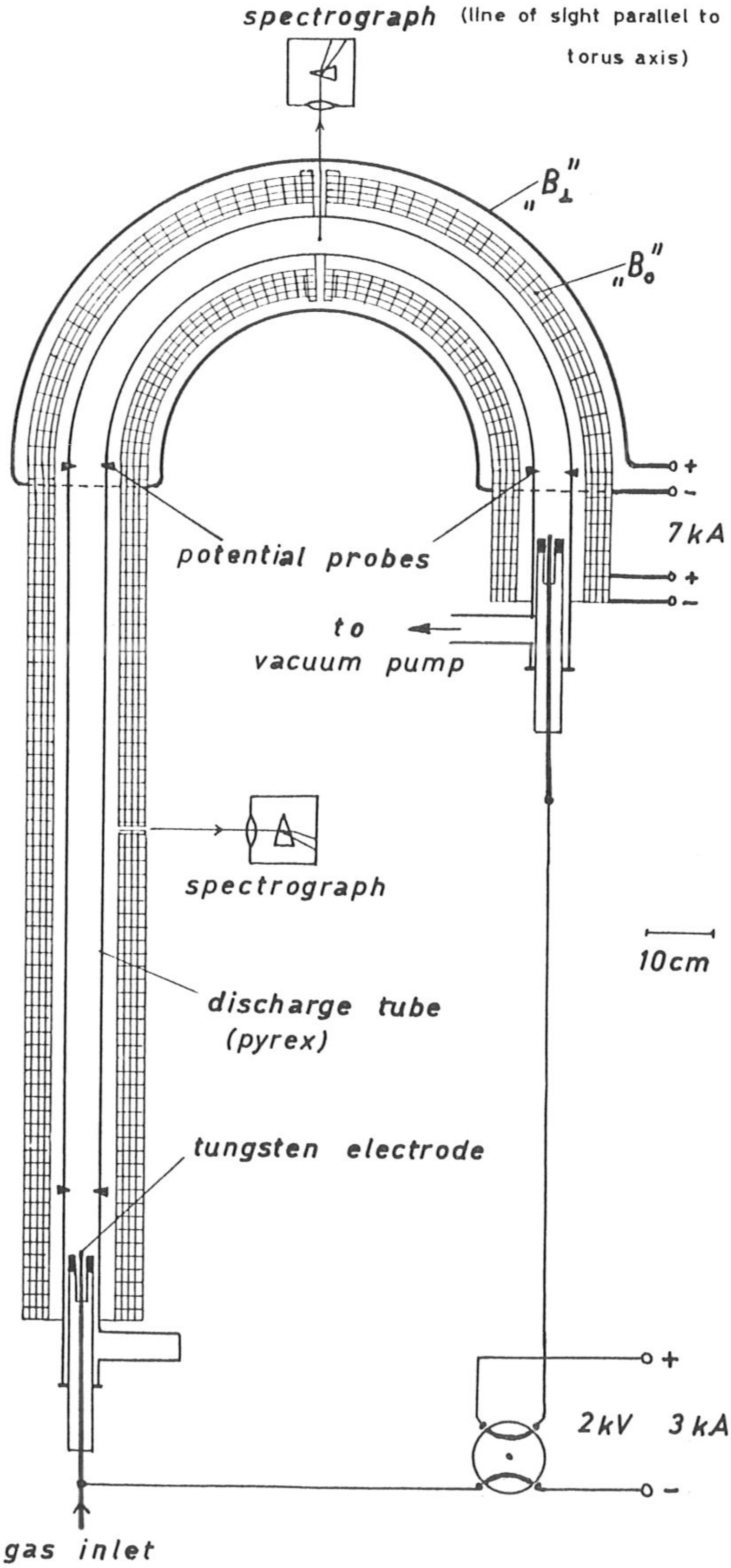


Fig. 2 Schematic of AMBIPOL IV

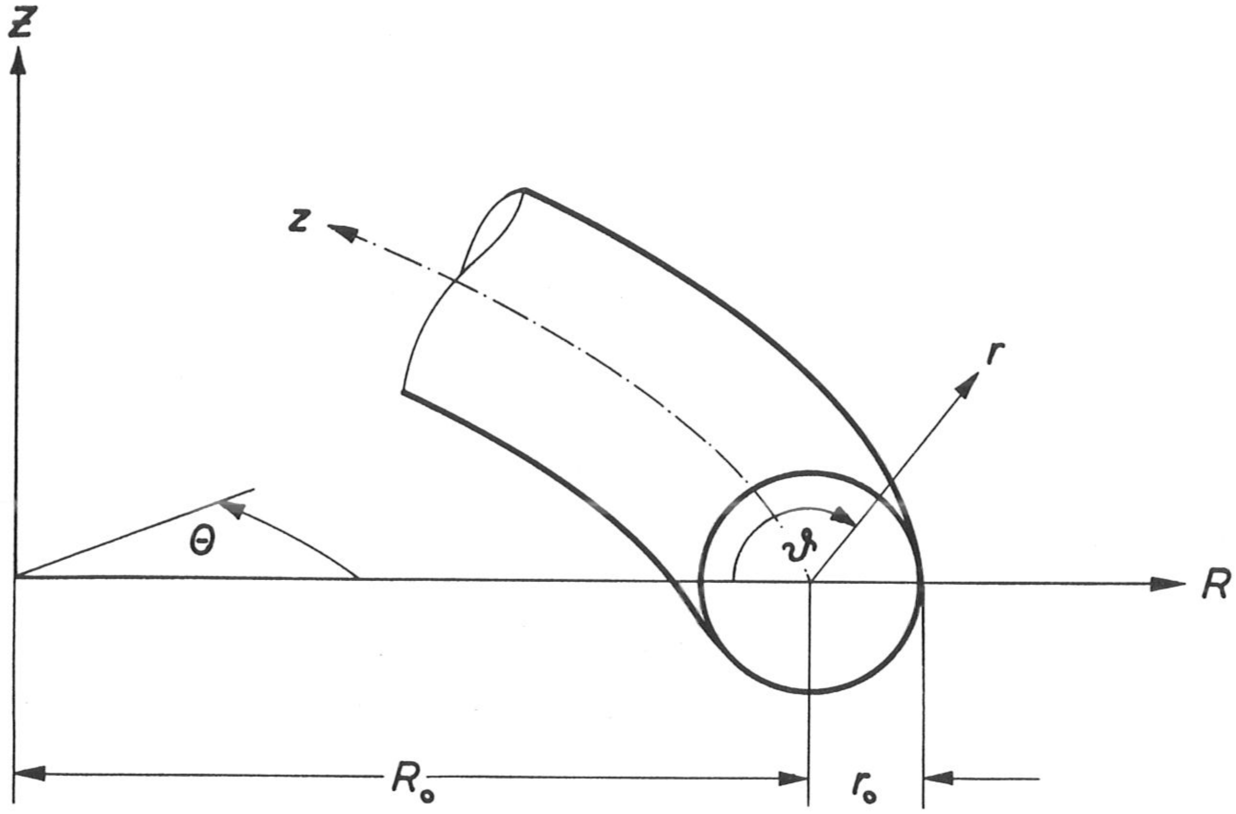


Fig. 3 Coordinate system used

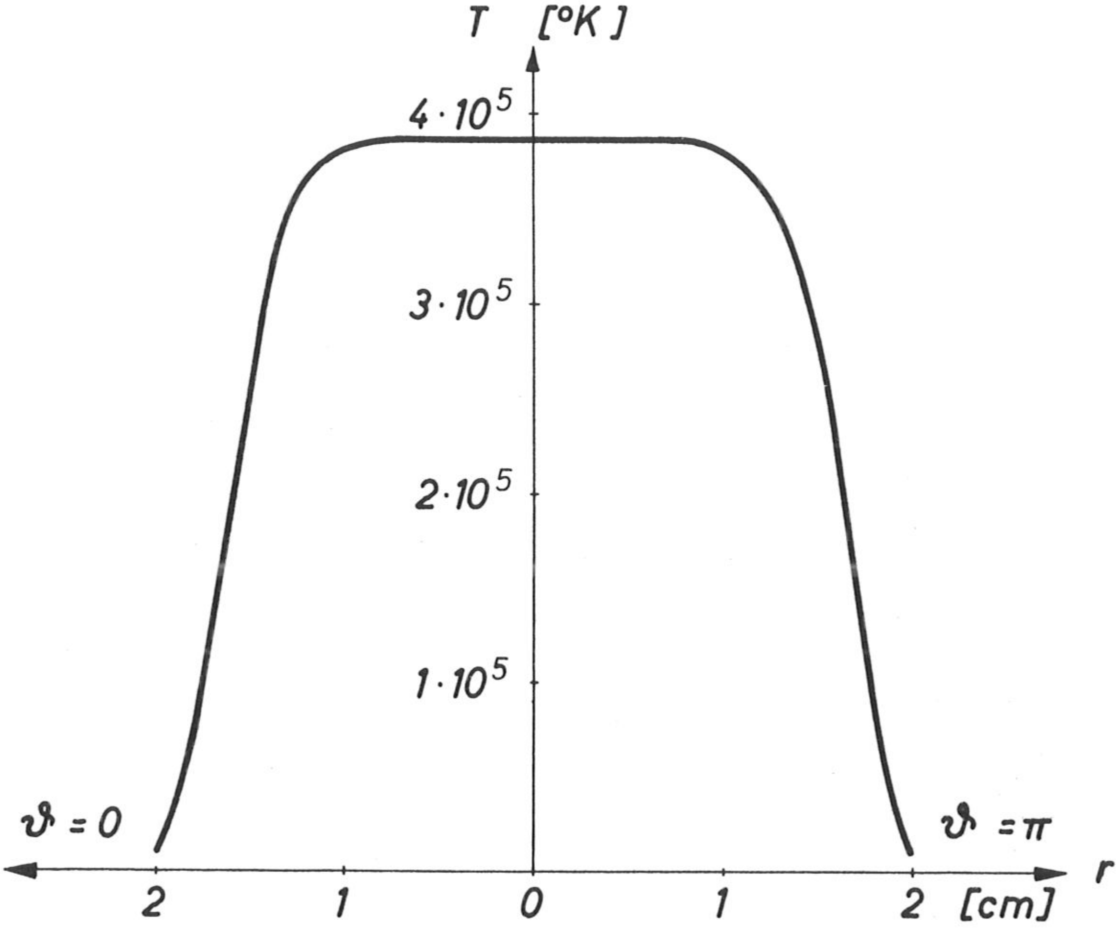
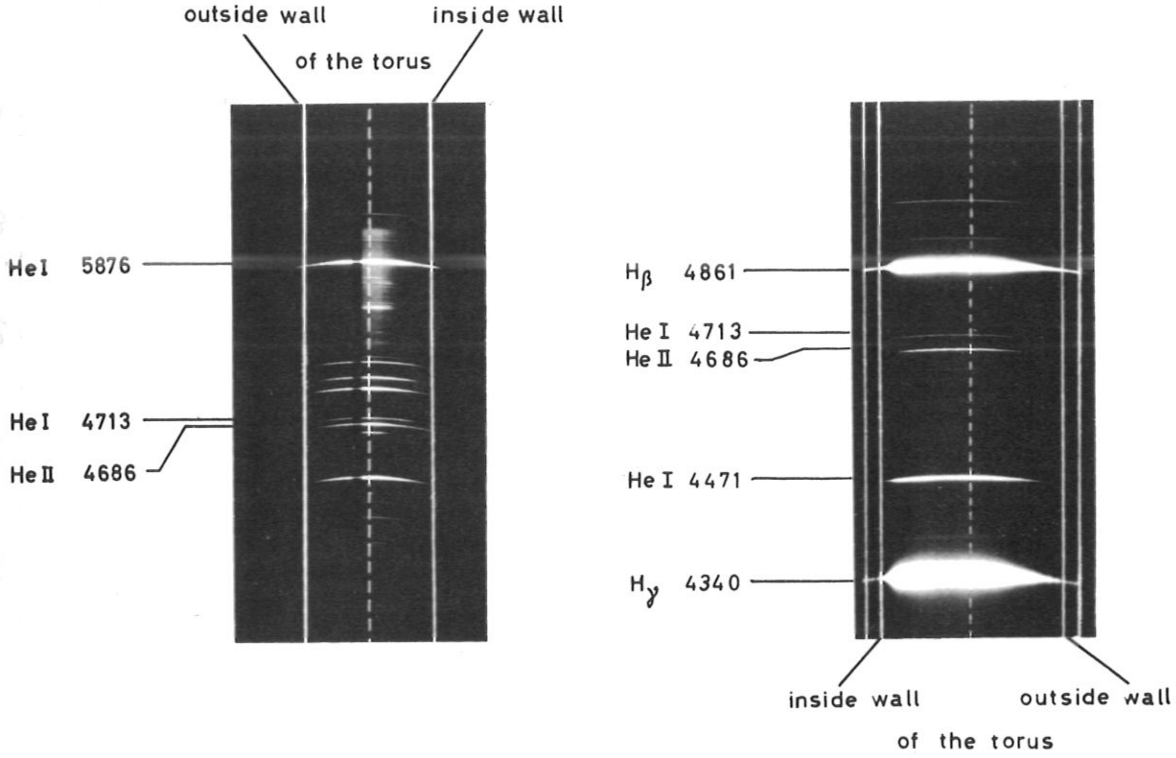


Fig. 4 Electron temperature profile at the discharge time t = 0.28 msec



EIERUHR K

AMBIPOL IV

Fig. 5 Side-on spectra of EIERUHR and AMBIPOL IV (line of sight parallel to torus axis)

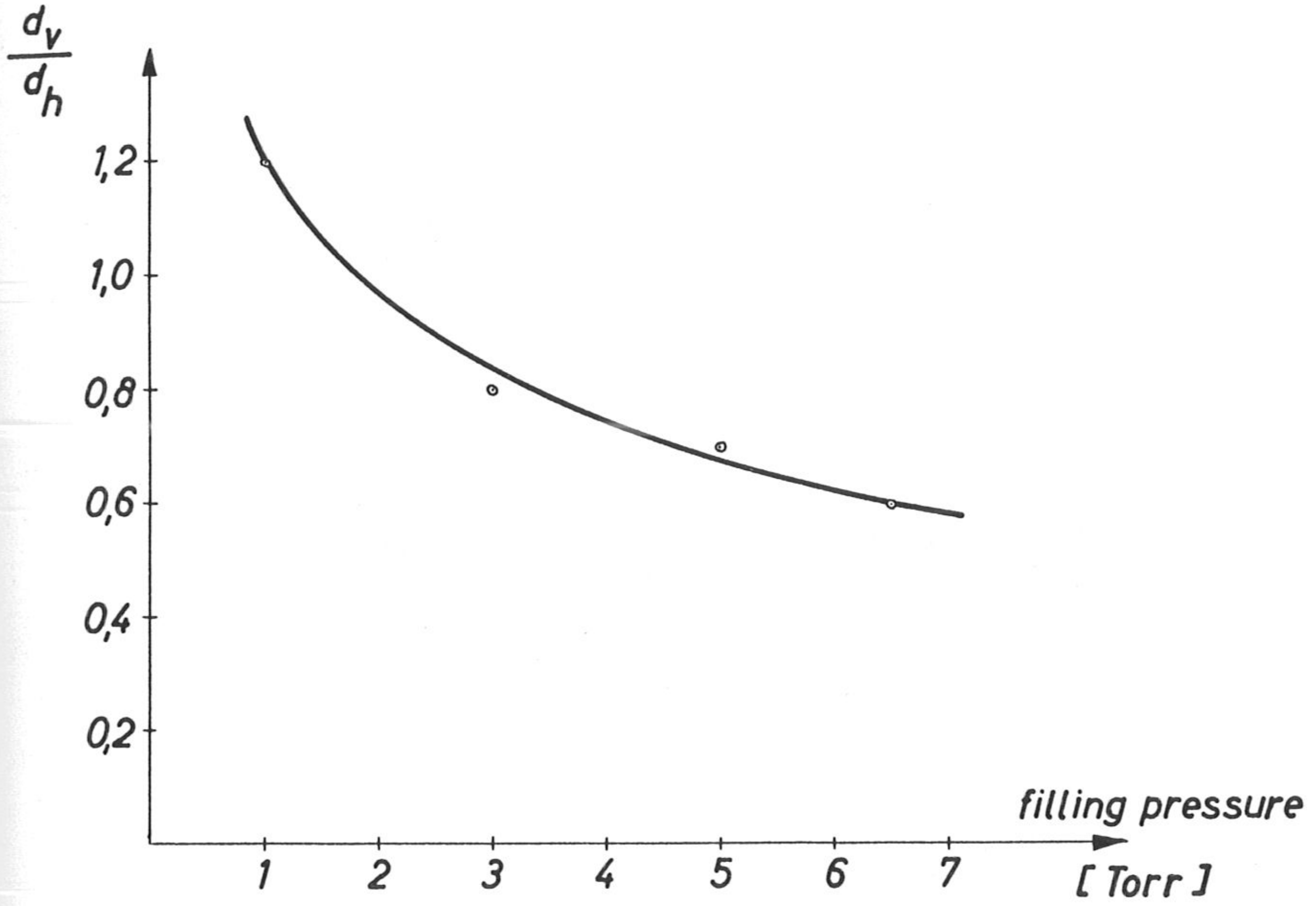
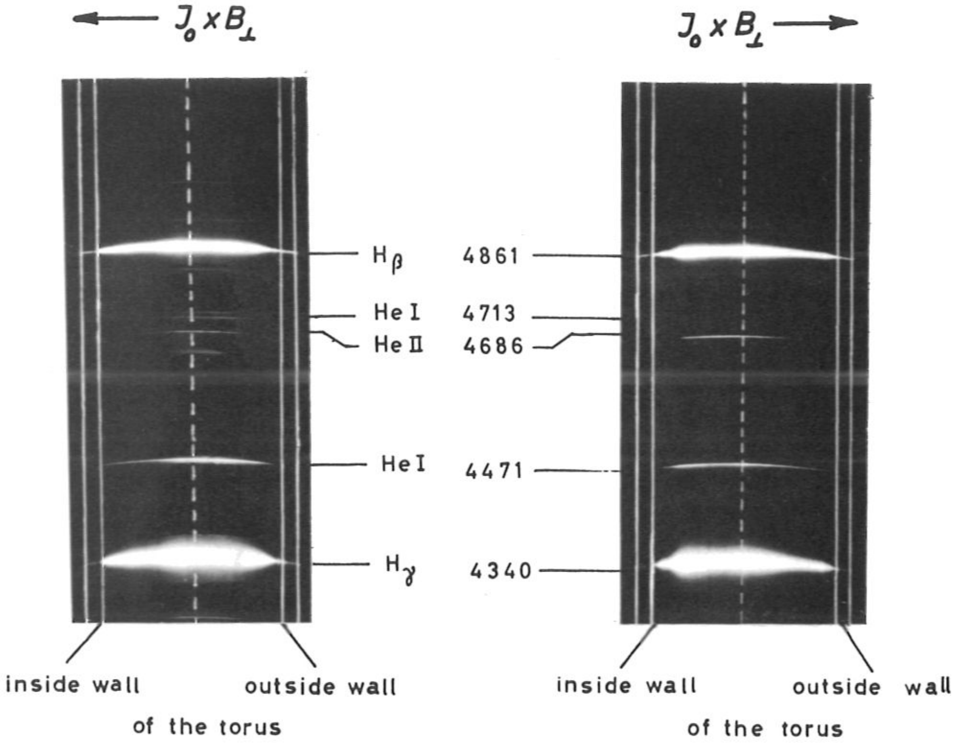


Fig. 6 Ratio of transverse dimensions of the plasma versus neutral gas pressure in EIERUHR K

d_v = dimension in the vertical direction (parallel to torus axis)

d_h = dimension in the horizontal direction (parallel to torus radius)



$B_\perp = 500$ G, $J_o = 2.5$ kA

Fig. 7 Influence of the transverse magnetic field on the side-on spectrum of AMBIPOL IV

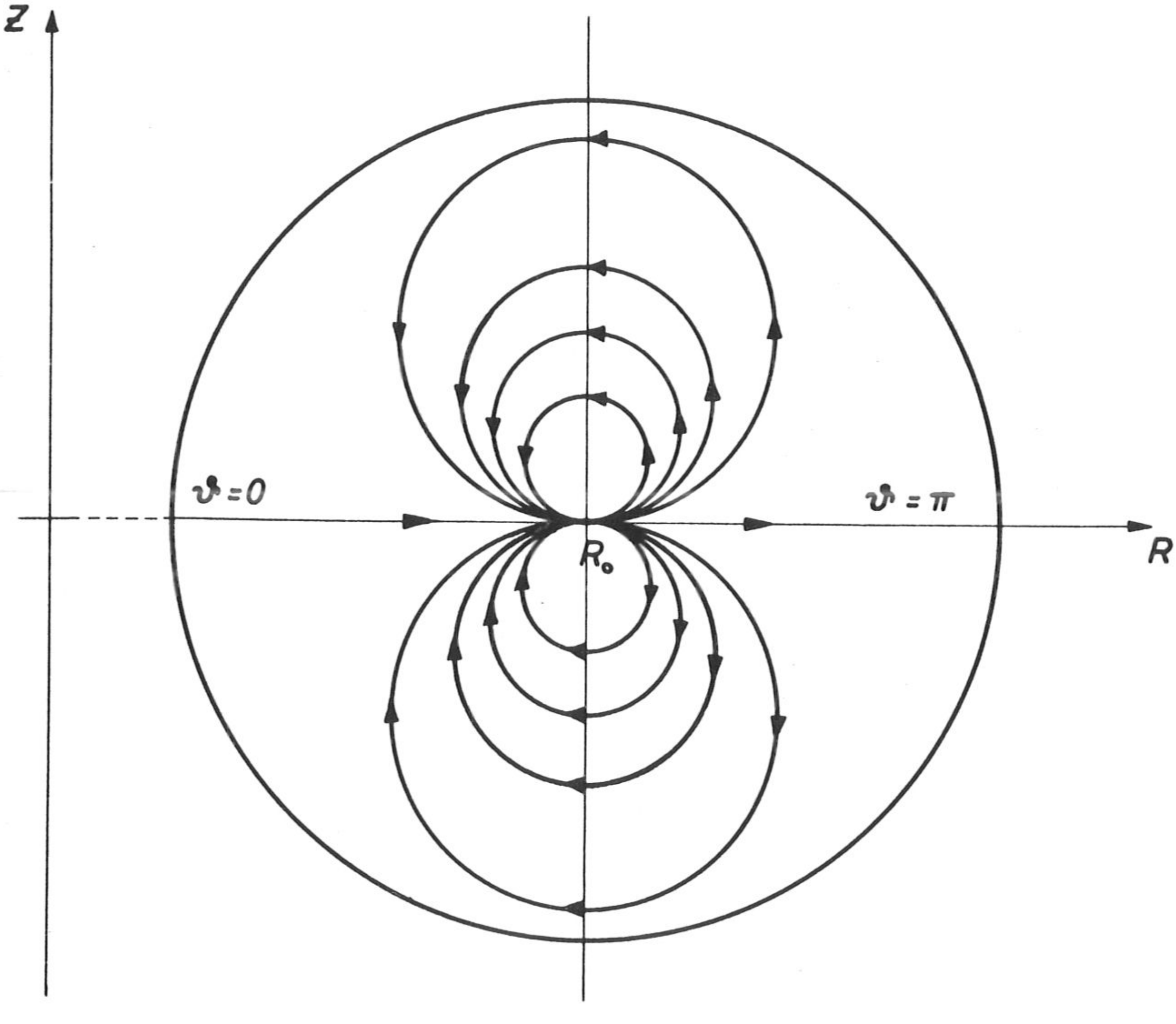


Fig. 8 Flow pattern in torus assuming classical diffusion

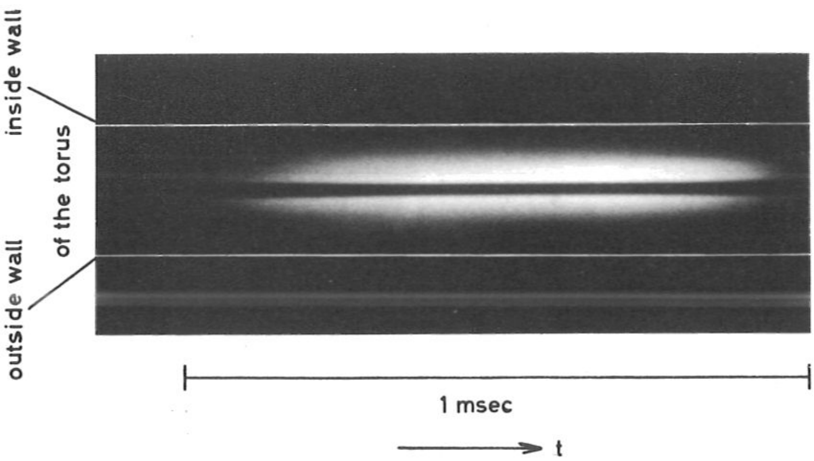


Fig. 9 Streak picture of the discharge in EIERUHR K in the light of He II (4686)