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EXPERIMENTS WITH A LARGE SIZED HOLLOW CATHODE DISCHARGE FED WITH ARGON, II

ANNUAL REPORT 1974

EURATOM - THE Group "Rotating Plasma"
EXPERIMENTS WITH A LARGE SIZED HOLLOW CATHODE DISCHARGE
FED WITH ARGON, II

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ABSTRACT

The results are presented of the measurements which we made on the positive column of a large sized Hollow Cathode Discharge in argon. The plasma is in a stationary state and fully ionized (though charge exchange collisions with neutral particles are still of importance). The ion temperature, $T_i$, may be varied between 1 and 40 eV and the plasma density, $n_e \leq 10^{14}$ part/cm$^3$, so that $\omega_{ci} T_i$ may be adjusted to values $> 1$. Besides $T_i$ and $n_e$ the electron temperature, $T_e$, the mass velocity, $v$, and the plasma potential, $\phi$, were measured together with the temperature, mass velocity and density of the neutral particles, all as function of radius and axial position.

The discharge parameters may be varied continuously: arc current, $I = 10 - 300$ A; gas feed, $Q = 0.2 - 8$ cm$^3$ NTP/s; magnetic field strength, $B = 500 - 5400$ Gauss and arc length $L = 25-250$ cm ($L$ is always $> \lambda$). Plasma columns of various diameters were generated by cathode tubes of 6, 9, 13 and 20 mm diameter (max. value of $d/r_{ci} = 6$).

A given set of discharge parameters corresponds to a certain set of plasma parameters and in this report the phenomenal relations between the plasma- and the gas discharge parameters are shown. It turns out that the experimentally determined relationship between plasma parameters is properly described by the momentum equations of ions and electrons. The angular mass velocity is heavily sheared, and equals the sum of the diamagnetic- and electric drift velocity of the ions. The conductivity of the plasma is "normal". The diffusion of the plasma through the magnetic field is in agreement with the "classical" diffusion theory and definitely not by mechanisms as suggested by Bohm (drain diffusion) and Simon (ion-ion collisions). As predicted by Kaufman the radial electric field points inward, but near the core of the arc it is four times larger than expected from ion-ion collisions alone.

The strong coherent low frequency oscillations which are generated spontaneously in the plasma are identified as $m = 1$ modes, but their origin is not quite clear yet -probably it are resistive drift oscillations. They may affect the radial density profile somewhat, but the plasma confinement is not deteriorated (the confinement time is about 2 ms).
EXPERIMENTS WITH A LARGE Sized HOLLOW Cathode Discharge FED WITH Argon, II

1. INTRODUCTION

In this report a survey is given of our measurements made on the positive column of a large sized HCD. The aim of our work was to determine experimentally all the plasma parameters in the column as function of radius and axial position and to compare the relationship between the measured values with the available theory (section 9). A cylindrical plasma, like the one present in an HCD, may be generated continuously, so that the plasma is in a stationary state. The attention is mainly directed to the d.c. values of the plasma parameters; the low frequency oscillations (ν = 10–20 Hz) which are generated spontaneously in the plasma, are described in section 8. An argon plasma was chosen because of the relatively large radii of the argon ions and the correspondingly broad density profiles; an extra advantage of argon is the low wear of the electrodes. The plasma density n_e(r,z), the ion temperature T_i(r,z), the electron temperature T_e(r,z), the mass velocity v(r,z) and the plasma potential Φ(r,z) were measured with the diagnostic tools which are described in a previous report (Lit. 1). To these Thomson scattering of Laser light was added in order to measure T_e and n_e in the core of the arc (see appendix).

The variable discharge parameters are arc current I (0–300 A), gas feed Q (0–8 cm³ NTP/s), magnetic field strength B (0–5400 Gauss) and arc length L (25–250 cm). The magnetic field strength has only a component in axial direction and is practically homogeneous (ΔB/B < 3%). As β = nKT/B²/8π < 4% the magnetic field strength may be considered as an independent external parameter. The length of the plasma column may be varied continuously and the core diameter was varied by using cathode tubes of various diameter, d.

A given set of discharge parameters corresponds to a certain set of plasma parameters. By varying one of the discharge parameters generally all plasma parameters are changed and a new equilibrium situation is created. E.g. by reducing the gas feed Q, the ion temperature, T_i, increases together with the radial electrical field strength, E_r, and the density, n_e, as well as its radial e-folding length decreases. The simultaneous changing of the plasma parameters requires great caution with the interpretation of the findings. In the following sections the phenomenal relations between the plasma- and the
discharge parameters are described. Under "standard conditions" L = 140 cm, 
d = 13 mm, B = 3400 Gauss, I = 100 A and Q = 4.5 cm³ NTP/s.

It is necessary to make a distinction between plasmas which are present in different regions of the discharge where different physical processes dominate. On the basis of the radial density profiles found previously (Lit.1) in radial direction a distinction is made between the core region (0 < r < d), the regular plasma region (d < r < rₖ) and the turbulent plasma region (r > rₖ). In the core region the plasma carries an appreciable current and the radial derivative of the density is small or even positive. In the regular plasma region the plasma behaves as expected from the usual two fluid model, whereas at radii larger than rₖ (4 to 5 cm from the axis) the plasma is turbulent. In axial direction we disregard the regions inside and directly in front of the cathode (∆z = 20 cm) and the region in front of the anode (∆z = 5 cm) where big voltage drops occur and where respectively ionization- and recombination processes are of particular importance. These regions are of course very essential for the existence of the plasma but are not the object of this study. We concentrate our attention to the positive column, which is most suited for studies in plasma physics.

The plasma density nₑ < 10¹⁴ part/cm². The neutral particle density, n₀, is lower than 3 x 10¹³ part/cm³ at the wall of the vacuum vessel. Pumping action of the discharge makes it an order of magnitude lower in the core region, so that n₀/nₑ < 3%. In the outside plasma regions n₀ may be larger than nₑ, but the plasma there may still be considered as "fully ionized" in the sense that Coulomb collisions occur more frequently than collisions with neutrals. Notwithstanding their relatively low density the neutral particles play an important role mainly because of charge transfer and -to a lesser degree- because of ionization processes.

The experiments were made with the same device as was used in our previous experiments. After some hesitation the tungsten plate was taken off from the anode assembly (Lit.1, Fig.2) so that the arc is in direct contact with the water cooled copper. This opened the possibility for operating the arc with higher currents (up to 300 A), lower gas feeds and lighter gases (helium and hydrogen). The application of Thomson scattering as a diagnostic tool required an additional section which gave the apparatus its full length (Lit.2, Fig.2).
2. THE ION TEMPERATURE, $T_i$

2.1. Radial dependence, $T_i(r)$

Like in the previous measurements (Lit. 1) $T_i$ was determined from Doppler-width measurements of the AII 4806 Å line. Other AII lines yield the same results and may be used as well. Under all conditions it was found that within the accuracy of the $T_i$ measurements ($\Delta T_i < 5\%$) the ion temperature is constant over the radius:

$$\frac{\partial T_i}{\partial r} = 0 \quad (1)$$

This result was found up to $r = 4$ cm, which is the upper limit to where the Doppler-width measurements can be made (see Fig. 7 of Lit. 2).

2.2. Axial dependence, $T_i(z)$

Fig. 1 shows the dependence of the ion temperature on the axial position in an arc of 140 cm length for two values of the gas feed ($Q = 1$ cm$^3$ NTP/s and $Q = 4.5$ cm$^3$ NTP/s) when the magnetic field strength $B = 3400$ Gauss. By inspection of this figure it should be realized that the cathode region extends about 20 cm in axial direction where it changes rather abruptly into the positive column which begins at $z = 0$. For both values of $Q$, $T_i$ varies approximately exponentially with $z$ with an e-fold length, $\lambda$, of about 60 cm.

$$T_i = (T_i)_z = 0 \cdot e^{-z/\lambda} \quad (2)$$

Apparently $\lambda$ does not depend much on $Q$. As $T_i$ depends strongly on $Q$ it follows that $\lambda$ does not depend much on $T_i$ either.

2.3. Length dependence, $T_i(L)$

Fig. 2 shows that for longer arcs $(T_i)_z = 0$ increases approximately linearly with arc length $L$ with a slope depending on $Q$

$$T_i \propto L \quad (L > 100 \text{ cm}) \quad (3)$$

This is similar to the findings of McNally and Skidmore (Lit. 3) with a carbon vacuum arc.

2.4. Dependence on arc current, $T_i(I)$

Fig. 3 shows a linear dependence of the ion temperature on arc current $I$ for cathodes of various diameters:
2.5. Influence of cathode diameter, $T_i(d)$

may also be derived from Fig. 3. The small diameter cathode ($d = 6$ mm) needs a higher current density than the cathodes of larger diameter to produce a plasma of certain temperature. This is illustrated in Fig. 3a where it can be seen that the plasma generated with the $d = 9$ mm and $d = 13$ mm cathodes rises 4.8 eV in temperature when the current density increases with 100 A/cm$^2$. The large diameter cathode ($d = 20$ mm) requires a smaller current density.

The large sized cathodes had somewhat different diameters and wall thicknesses; apparently the ion temperature depends also somewhat on the wall thickness.

2.6. Dependence on gas feed, $T_i(Q)$

is shown in Fig. 4a for the $d = 13$ mm cathode operated with $I = 100$ A and $B = 3400$ Gauss. The measurements were made with an arc of 140 cm length at $z = 50$ cm. Similar curves were found for other cathode diameters. If $Q/(\pi/4)d^2$ is used as parameter all curves coincidence within the error limits. This indicates that the ion temperature, $T_i$, is a function of the gas flux \((n_v)_\text{gas} = Q/(\pi/4)d^2\).

Fig. 4b shows the dependence of $(T_i)_{z=0}$ on gas feed, $Q$, for arcs of various lengths, $L$.

Both figures show little variation of $T_i$ with $Q$ for values of $Q$ above 4 to 5 cm$^3$ NTP/s. For this reason a gas inlet $Q = 4.5$ cm$^3$ NTP/s was chosen as standard condition.

2.7. Dependence on magnetic field strength, $T_i(B)$

is shown in Fig. 5 for two values of gas feed $Q$ (1 cm$^3$ NTP/s and 4.5 cm$^3$ NTP/s). For $Q = 1$ cm$^3$ NTP/s the ion temperature is about one and a half times the value found for $Q = 4.5$ cm$^3$ NTP/s, but the shape of the curves is the same. Below $B = 3400$ Gauss the temperature increases with $B$, at higher $B$ values $T_i$ is approximately independent of $B$. For this reason a magnetic field strength of $B = 3400$ Gauss was chosen as standard condition. (For low $B$ measurements see Lit.4.)
The heating mechanism of the ions is unknown. Apparently the heating takes place in the cathode region and it is of interest to know how it is affected by the cathode diameter, d. The ion temperatures of the plasma columns generated with cathode tubes of various diameter, fed with the same gas flux and with currents adjusted in accordance with Fig. 3, all depend in the same way on B. This indicates that the shape of the $T_i(B)$ curve is not determined by the relation $2r_i/d = 1$.

3. THE PLASMA DENSITY, $n_e$

In the regular plasma region the plasma density may be measured with Langmuir probes (see Lit. 1). The core region is not accessible for Langmuir probes and for this reason Thomson scattering experiments were prepared (see section 10). The plasma density and the electron temperature in the core region are in such a range ($n_e \ll 10^{14}$ part/cm$^3$; $T_e \ll 10$ eV) that the inaccuracy in the scattering experiments leads to an uncertainty of a factor two in the plasma density.

3.1. Radial dependence, $n_e(r)$

Previous measurements with a big flat probe (5 mm diameter, 2 mm thick) made in the regular plasma region yielded approximately Gaussian-shaped density profiles:

$$n_e(r) = n_e(0)e^{-r^2/q^2}$$

(5)

with $q$ depending on the magnetic field strength, $B$, and gas feed, $Q$. For $B$ values above about 3000 Gauss $q^2$ seems to vary inversely proportional to $B$ ($q^2 = 6.4$ at $B = 3400$ Gauss and $q^2 = 4.2$ at $B = 5100$ Gauss). $n_e(0) < 10^{14}$ part/cm$^3$ also depending on $B$ and $Q$. In order to improve the spatial resolution, much smaller Langmuir probes (1 mm diameter, 1 mm thick) were introduced into the plasma. The probe characteristics of these probes show a well saturated ion current and also saturation of the electron current (Fig. 6). They revealed the presence of small dents in the overall Gaussian profiles (Fig. 7). These deviations from the Gaussian profiles are possibly related to the low frequency oscillations which are generated spontaneously in the plasma (see section 8).

The radial density profiles measured at $z = 5, 20, 35, ..., 115, 130$ cm all have the same shape, but apparently $q^2$ increases somewhat towards the anode. (Under standard conditions $q^2 = 8.5$ cm$^2$ at $z = 100$ cm.)
3.2. Axial dependence, $n_e(z)$

A proper understanding of the plasma column requires knowledge of the axial variation of the plasma density; the more so as it turned out that some other plasma parameters vary along the axis of the arc. During the $n_e(r)$ measurements mentioned in the preceding section it was found that the variation along the axis of the ion saturation current to the probe is everywhere less than a factor 2, indicating that $n_e$ does not vary much with $z$.

Langmuir probe measurements in axial direction require either a probe moving along the axis of the plasma column or the plasma column moving along a fixed probe (which we did). Because of the strong radial variation of the density the radial position of the probe must be fixed accurately within 1 mm all along the axis (corresponding to a deviation in $n_e$ of about 10%). Neither of these methods gives the required accuracy over a length of 1 to 2 meter. For that reason a movable ringshaped wire was mounted around the arc (8 cm diameter), adjustable in the vertical plane (Fig. 8). Its characteristic is similar to the characteristic of a Langmuir probe. The current to the ring is at minimum when its centre coincides with the axis of the arc (Fig. 8a). This minimum current was measured at several distances along the axis. The accuracy improves with $B$. The result of these measurements is shown in Fig. 9; at $r = 4$ cm the plasma density increases somewhat with $z$ (in the direction of the anode*). This in agreement with the "less accurate" previous results.

In the regular plasma region the plasma density varies only weakly along the axis:

$$\frac{L}{n_e} \left| \frac{\partial n_e}{\partial z} \right| \ll 1.0$$

(6)

The Thomson scattering experiments indicate that equation (6) holds also in the core of the arc.

*) $n(z)$ is certainly not a sinusoidal function of $z$, $n(z) = \sin \frac{\pi z}{L}$, as was assumed (but not measured) by Simon (Lit. 5) in order to account for the particle diffusion in a comparable arc.
3.3. Dependence on gas feed, $n_e(Q)$

Both Langmuir probe- and Thomson scattering measurements show unambiguously that the plasma density increases with $Q$. Not only $n_e(0)$ of equation (5) increases with $Q$ but also $q^2$, as is shown in Fig. 10. For $Q < 2 \text{ cm}^3 \text{ NTP/s}$, $q^2$ decreases with decreasing $Q$ whereas for $Q > 2 \text{ cm}^3 \text{ NTP/s}$, $q^2$ does not change much and neither does $n_e(0)$. From Fig. 4 we know that lowering of $Q$ causes an increase of $T_e$. The perpendicular diffusion coefficient, $D_p$, is proportional to $n_e T_e^{-\frac{1}{2}}$ so that we expect $D_p$ to decrease with decreasing $Q$ ($T_e$ will certainly not decrease with increasing $T_i$). This explains qualitatively the decrease of $q^2$ with decreasing $Q$. The improved radial confinement does not go along, however, with an increase of $n_e(0)$ as the plasma production lowers with decreasing $Q$.

3.4. Dependence on magnetic field strength, $n_e(B)$

As was already mentioned in section 3.1, for values of $B > 3000$ Gauss:

$$q^2 = B^{-\frac{1}{2}}$$  \hspace{1cm} (7)

The improved radial confinement with $B$ leads to somewhat higher values of $n_e(0)$ as may be seen from Fig. 10a-c of Lit.1 (see also section 9).

3.5. Dependence on arc current, $n_e(I)$

Under standard conditions the ion saturation current to a Langmuir probe increases about a factor two when the arc current is doubled from 100 A to 200 A. The shape of the radial density curve does not change noticeably, so that it may be conjectured that the main effect of increasing $I$ is a (linear) increase of $T_i$, whereas $n_e$ increases with the square root of $I$. Thomson scattering experiments seem to confirm this surmise.

3.6. Dependence on arc length, $L$, and cathode diameter, $d$

Langmuir probe measurements indicate that the plasma density does not depend much on $L$, but that $n_e$ increases somewhat with $d$ (current density and gas flux being the same).
4. THE ELECTRIC POTENTIAL

The radial electric field in the core region is rather well known, due to the fact that the plasma rotation in this region is mainly connected to electric drift velocity (see section 9). All measurements which are made with Langmuir probes in the regular plasma region indicate that for \( r > 2 \) cm the electron temperature is approximately constant \( T_e = 1.5 \) to \( 2 \) eV independent of \( r \) and \( z \) (see section 6). As the ion temperature is also constant in radial direction (eq. (1)) the radial electric field may be well derived from the floating potential, \( V_{fl} \). The axial electric field in the core region may be determined from the variation of the arc voltage with arc length (see section 4.3).

The combined measurements make the electric field in the positive column rather well known. For an understanding of the overall performance of the discharge a complete knowledge of the equipotential surfaces in the discharge is required. This is difficult to obtain, particularly in the cathode region which is of such a vital importance for the generation of the plasma. A tentative drawing of the equipotential lines in a plane through the discharge axis is shown in Fig. 11. The power supply of the arc is not grounded, but the anode always floats to about earth potential. The equipotential surfaces are concentrated near the cathode and "escape" through the vacuum ring of the cathode support. The big voltage drop at the cathode region is required for the plasma generation\(^*\). If the cathode would assume earth potential, the equipotential surfaces had to "leave" the vacuum chamber at the vacuum ring of the anode support. The strong electric fields in the core region would then point radially outward, which would work out detrimental for the confinement of the ions. Thus a potential distribution as sketched in Fig. 11 with the anode floated to earth is most favorable for the plasma generation in the cathode. It is also clear that it does not make much difference whether the (isolated) sections of the vacuum chamber are grounded or not; when floating they assume approximately earth potential anyhow. (Under standard conditions the section at the anode side assumes a floating potential

\(^*\) The strong electric fields in the neighborhood of the cathode support lead easily to spurious discharges in this region which may be prevented by slipping a pyrex glass tube around the cathode support.
of + 3.4 V relatively to earth, the other sections respectively 2.4, 2.5 and 1.5 V; if grounded the currents to the sections amount respectively to 17, 50, 54 and 160 mA).

Fig. 12 shows the I-V characteristic of the arc under standard conditions.

4.1. The voltage distribution along the z axis, V(z)

at the centre of the HCD discharge (r = 0) is depicted tentatively in Fig. 11a. Most of the voltage drop at the cathode occurs inside the hollow cathode tube. The positive column is a very good conductor: for an arc length of 1 to 2 m the voltage drop over the positive column is 10–20 V when the arc current is 100–200 Amp. A way of measuring E_z is described in section 4.3.

The luminosity of the plasma in front of the cathode is lower than along the positive column. This may be related to a small "dip" in the V(z) curve like occurs in the Faraday dark space of a glow discharge. The presence of such a dip is not established definitely.

4.2. The voltage distribution in radial direction, V(r)

for various values of B was already shown in Fig. 11 of Lit. 1. One to two cm from the core the radial electric field is large and directed inwardly corresponding to a rotation of the plasma in the direction of the electrons. Fig. 13 shows the radial electric field as function of radius; together with the space charge density \( \rho = (1/4 \pi) \) div \( E \) (in electron charge units).

4.3. Variation with arc length, V(L)

Fig. 14 shows the arc voltage for various values of arc length, L. From these measurements the axial electric field in the core region may be estimated. It may be expected that like in the glow discharge the voltage drops at the anode and at the cathode are not changed noticeably when the length of the discharge is changed. The measured variation of the voltage drop over the discharge, \( \Delta V \), equals the variation of \( V \) over the positive column. As \( T_e \) varies with \( L \), \( \Delta V \), is not only brought along by a variation in length, but also by a variation of the conductivity.
\[
\sigma = \sigma_0(L)e^{-\frac{3\pi}{2\lambda}} \quad \text{with} \quad \sigma_0(L) = L^{3/2}
\]
so that:
\[
V = \int_0^{L_c} E_z \, dz = \frac{1}{\sigma_0(L)} \frac{2\lambda}{3} (e^{\frac{3L_c}{2\lambda}} - 1) = \frac{1}{\sigma_0(L)} \frac{2\lambda}{3} e^{\frac{3L_c}{2\lambda}} (L_c/\lambda \gg 2)
\]
where \(L_c\) is the length of the positive column \((L_c = L - 20)\)
\[
\frac{dV}{dL} = \frac{j}{\sigma_0} \left(1 - \frac{\lambda}{L}\right) e^{\frac{3L_c}{2\lambda}}
\]
Under standard conditions, \(L = 140\) cm, \(\lambda = 60\) cm and \(dV/dL = 0.15\) V/cm.
In order to calculate the current density, one ion Larmor radius
\((r_{ci} = 0.5\) cm\) may be added to the radius of the cathode \((d/2 = 0.65\) cm\).
Thus the current of 100 A flows over an area of about 4 cm² so that
\(j = 25\) A/cm². Equation (6) yields: \(\sigma_0 = 1600\) \(\Omega^{-1}\) cm⁻¹. Theoretically
\(\sigma = 20\) \(\text{T}_e^{3/2}\) (Lit. 5) which leads to \((\text{T}_e)_{Z = 0} = 18\) eV in agreement with
the Thomson scattering experiments (see section 6). This seems a strong
indication that the electric conductivity of the plasma in the core
region is "classical".

4.4. Variation with gas feed, \(V(Q)\)

is shown in Fig. 15. With increasing \(Q\) the temperature and the
conductivity of the plasma decreases and \(E_z\) in the positive column is
expected to increase. Thus the decrease in the arc voltage with
increasing \(Q\) must have its origin in the cathode region. The neutral
particle density there increases with \(Q\) so that a lower voltage drop
\(\Delta V\) (cathode) is required to ionize the gas. The lower \(\Delta V\) (cathode) is
accompanied by a lower temperature of the plasma particles in the positive
column, but the end effect is a decrease of \(V_{\text{arc}}\) with \(Q\). A similar
indication is obtained from Fig. 14 which shows that \(dV/dL\) for
\(Q = 4.5\) cm³ NTP/s is somewhat lower than for \(Q = 1\) cm³ NTP/s.

The measurements of the angular velocity in the core region show
that in the core region the radial electric field \(E_r\) does not depend
much on \(Q\). Probe measurements made in the regular plasma region show that
in this region \(E_r\) neither depends much on \(Q\).
4.5. Variation with magnetic field strength, $V(B)$

Fig. 16 shows that $V_{\text{arc}}$ raises with $B$. As the plasma temperature does not vary with $B$ for $B > 3000$ Gauss the increase of $V_{\text{arc}}$ with $B$ may only be explained by a decrease of the area, $A$, through which the current, $I$, flows, like was suggested in Lit. 6. With $A = \pi (d/2 + r_{ci})^2$ the axial electric field $E_z = I/\sigma A$ is expected to be at $B = 3400$ Gauss a factor 1.5 higher than at $B = 5100$ Gauss. Fig. 16 indicates a larger increase of $E_z$, whereas $dV/dL$ measurements indicated an increase of only a factor 1.25. The discrepancies probably arise from the simplification to take for the ion Larmor radius, $r_{ci}$, a fixed value.

Above $B = 3000$ Gauss the angular mass velocity in the core region does not change noticeably with $B$, which indicates that in this region $E_z \sim B$. Probe measurements in the regular plasma region (Fig. 11, Lit. 1) show that in the region next to the core region $E_z$ also increases with $B$. The negative space charge density in the core region clearly increases with $B$.

5. THE ANGULAR MASS VELOCITY $\Omega$

5.1. Radial dependence, $\Omega(r)$

Improvements in the adjustment and the temperature control of the étalon Fabry Perot spectrometer (spacing 1 mm) opened the possibility to measure $v_\theta = \Omega r$ up to $r = 4$ cm from the axis with a limit of detection of about $1.5 \times 10^4$ cm/s ($\Delta \lambda = 2.5 \text{ m}\AA$). The optical measurements now overlap the pendulum measurements which are made in the region $2 \text{ cm} < r < 6 \text{ cm}$. The $\Omega(r)$ curves of Lit. 1 are shown again in Fig. 17 with the extended Doppler shift measurements added. In the core region the angular velocity, referred to as $\Omega_0$, is constant and in the direction of the electrons. In the regular plasma region $\Omega$ is strongly sheared and changes sign at $r = 3$ cm.

5.2. Axial dependence, $\Omega(z)$

For all values of $z$ the $\Omega(r)$ curves are of the same shape, but the absolute value of $\Omega$ decreases with $z$. Fig. 18 shows $\Omega_0$ as function of $z$ for two values of the gas feed ($Q = 4.5 \text{ cm}^3 \text{ NTP/s}$ and $Q = 1 \text{ cm}^3 \text{ NTP/s}$). Apparently $\Omega_0$ does not depend strongly on $Q$ and decreases approximately
linearly with $z$. For $L = 140$ cm and $B = 3400$ Gauss.

$$\Omega_0 = 5 \times 10^5 (1 - 10^{-2} z) \text{ rad/s}$$  \hspace{1cm} (9)

Though the measurements indicate an exponential $z$ dependence of $T_i$, the variations of $T_i$ and $\Omega_0$ with $z$ are rather alike and within the error limits it is still possible that $\Omega_0$ is proportional to $T_i$.

5.3. Dependence of magnetic field strength, $\Omega(B)$

Fig. 19 shows the variation of $\Omega_0$ with $B$ for two values of $Q$. The shape of the curves resembles the shape of the $T_i(B)$ curves, which indicates that $\Omega_0$ and $T_i$ depend approximately in the same way on $B$.

The dependence of the radial $\Omega$ profile on $B$ is shown in Fig. 18.

5.4. Dependence on gas feed, $\Omega(Q)$

Fig. 20 shows the variation of $\Omega_0$ with $Q$. Like $T_i$, $\Omega_0$ increases with decreasing values of $Q$ but less drastically. For $Q > 3$ cm$^3$ NTP/s, $\Omega_0$ is approximately $2/3 T_i$ [eV] $\times 10^5$ rad/s ($z = 50$ cm, $d = 13$ mm cathode, $I = 100$ A). For lower $Q$ values the factor of proportionality becomes lower.

5.5. Dependence on discharge current, $\Omega(I)$

Fig. 21 shows the variation of $\Omega_0$ and $T_i$ with $I$ for the $d = 20$ mm cathode ($z = 50$ cm). For values of $I > 150$ A, $\Omega_0$ increases linearly with $I$ like $T_i$ and

$$\Omega_0 = 0.54 T_i \text{ [eV]} \times 10^5 \text{ rad/s}$$  \hspace{1cm} (10)

5.6. Dependence on arc length, $\Omega(L)$

Fig. 22 shows that $\Omega_0$ varies linearly with $L$ and that equation (10) holds approximately.

5.7. Influence of cathode diameter, $\Omega(d)$

The plasma is mainly generated inside the hollow cathode by a mechanism which is not known exactly - neither $T_i$ nor $\Omega_0$ can be predicted theoretically. Comparing cathodes of various diameters seems to be most meaningful if gas flux and current density are the same.
From section 2.5 we know, however, that under these conditions the larger (smaller) cathode generates a plasma of higher (lower) temperature. For that reason we operated the various cathodes \((d = 6, 9, 13 \text { and } 20 \text{ mm})\) with the same gas flux\(^{*)}\), but chose the current in such a way that the temperature of the plasma was approximately the same \((T_i \approx 4 \text{ eV at } z = 50 \text{ cm for } B = 3400 \text{ Gauss and } L = 140 \text{ cm})\). The \(T_i(B)\) curves found under these conditions all coincidence practically with Fig. 5. The corresponding \(\Omega_0(B)\) curves have the same shape, but the \(\Omega_0\) values found for the various cathodes were different. The results are summarized in Table I.

Table I

| \(\Omega_0/T_i\) ratios for cathodes of various diameters measured at \(z = 50 \text{ cm}\) and \(z = 0 \text{ cm}\). \(B = 3400 \text{ Gauss, } L = 140 \text{ cm}. \Omega_0\) in units of \(10^5 \text{ rad/s}\). |
|---|---|---|---|---|
| \(d = 6 \text{ cm}\) | \(d = 9 \text{ cm}\) | \(d = 13 \text{ cm}\) | \(d = 20 \text{ cm}\) |
| \(Q \text{ cm}^3 \text{ NTP/s}\) | 1 | 2 | 4.5 | 8\(^{*)}\) |
| I Amp | 40 | 50 | 100 | 170 |
| \(T_i(z = 50 \text{ cm})\text{eV}\) | 3.5 | 4.0 | 3.7 | 3.6 |
| \(\Omega_0(z = 50 \text{ cm})\) | 3.7 | 2.9 | 2.5 | 1.9 |
| \((\Omega_0/T_i)z = 50 \text{ cm}\) \(\Omega_0(z = 0)\) | 0.95 | 0.73 | 0.67 | 0.54 |
| \(T_i(z = 0)\text{eV}\) | 11.5 | 8.5 | 8.5 | - |
| \(\Omega_0(z = 0)\) | 7.6 | 4.7 | 4.5 | - |
| \((\Omega_0/T_i)z = 0\) | 0.66 | 0.55 | 0.53 | - |

When operated in such a way that at \(z = 50 \text{ cm}\ \(T_i\) is approximately the same, the plasma generated by the smaller diameter cathodes rotates relatively faster.

\(^{*)}\text{ The pumping capacity of the vacuum system allows a gas feed of maximum 8 cm}^3 \text{ NTP/s, so that the } d = 20 \text{ m cathode was operated with a somewhat too small a gas flux.}\)
6. THE NEUTRAL PARTICLES

The neutral particles enter the apparatus through the hollow cathode and flow into an active zone, where the larger part is transformed into plasma particles in a way which is still not exactly known. In the core of the positive column the neutral particles are relatively rare (about 1%) but nevertheless they play an important role insofar as they cause the variation of the ion temperature along the axis. In the outside regions of the arc where Coulomb collisions no longer dominate, self-evidently the neutral particles have to be also taken in consideration.

6.1. The neutral particles in the cathode region

The hollow cathode tube may be divided into (a) a cool region (gas temperature $T_n(1) = 300^\circ C$) and (2) a hot region (gas temperature $T_n(2) = 1800^\circ C$). The gas pressure in the cool region may be measured; under standard conditions it was found to be about 2 Torr so that the neutral particle density in the cool region is $n_n^{(1)} = 6 \times 10^{16}$ part/cm$^3$.

As the cathode diameter, $d$, is large compared to the mean free path length for collisions between the neutrals, $n_n^{(2)} = (T_n^{(1)}/T_n^{(2)}) n_n^{(1)} = 10^{16}$ part/cm$^3$. With a $(e, n)$ cross section for ionization $\sigma = 3 \times 10^{-16}$ cm$^2$, $\lambda$ (ionization) is found to be about 1/3 cm, or $d/4$ in agreement with other observations (Lit. 6).

The gas feed, $Q$, corresponds to a flow of about $10^{20}$ part/s cm$^2$ so that the axial velocity of the neutral particles in the hot region is $v_n^{(2)} = 10^4$ cm/s. With this velocity the particles enter the active zone where they are ionized and accelerated in the direction of the anode to velocities of about $v_i// = 6 \times 10^4$ cm/s. An acceleration of the ions in the direction of the anode may be explained on the basis of Fig. 11a.

The ionization of the neutral particles takes mainly place at the top of the "hill" of the $V(z)$ curve, where the electrons have acquired an energy of about 50 eV (which corresponds to the optimum for ionization in Argon).

6.2. The neutral particles in the positive column

In the spectral range of the Fabry Perot spectrometer ($3500 \AA$ - $5000 \AA$) the intensity of the strongest AI lines is two orders of magnitude less than the intensity of the strongest AII lines. The background noise amounts
to 10 - 20% of the peak value of the Al lines. Outside the core region the line intensity drops rapidly and soon disappears in the noise. Doppler shift measurements can only be made in the core region and Doppler width measurements up to a radius of about 1.5 cm. All Al lines show the same Doppler loading. The Al 4201 Å line was chosen for making the T_n(r, z) and $\Omega_0n$ measurements.

The angular velocity of the neutral particles in the core region was found to be the same as the angular velocity of the ions (within the accuracy of the measurements of about 10%).

$$\Omega_0n = \Omega_0i$$

Accordingly the temperature of the neutral particles on the axis, $T_n(0)$ is everywhere equal to the ion temperature:

$$T_n(0) = T_i(0)$$

for all values of z

(Apparently the Doppler width of the neutral Al lines emitted from the core region is determined by neutral particles which originate from charge exchange or recombination. Outside the core region the temperature of the neutral particles drops rapidly (see Fig. 23).)

From the spectroscopical observations the neutral particle density in the core region is estimated to be $n_n(0) = 10^{12}$ part/cm$^3$. In the neighbourhood of the wall the neutral gas pressure is about $7 \times 10^{-4}$ Torr and $n_n \approx 2 \times 10^{13}$ part/cm$^3$. Some indication about the value of $n_n$ at intermediate radii was obtained by introducing a tantalum tube ($\phi = 6$ mm) into the plasma and by measuring the pressure at the other end of this tube, $p_n$, as function of the radial position of the snout$^*$. Fig. 23 shows $p_n(r)$, together with the most probable variation of $n_n$ with $r$ between its values in the core and at the wall. Outside the core $n_n(r)$ drops exponentially with an e-folding length of about 0.6 cm. The arc clearly works as a pump.

Pendulum measurements which were used before for determination of the angular mass velocity (Lit. 1), may also be used to determine the axial velocity of the plasma, $v_z$. It was found that in the neighbourhood of the core $v_z = (6 \pm 2) \times 10^4$ cm/s all along the axis (up to some cm in front of the anode). This is in agreement with the Doppler shift measurements made by van der Sijde and Tielemans (Lit. 7).

*) At $r = 2$ cm the snout becomes glowing and at $r = 1$ cm it is white hot.
A discussion of the axial mass velocity of the plasma, which is of importance for a proper understanding of the particle and energy balance in the arc is given in section 9. Here it will be considered only in connection with the neutral particles which hit the core of the arc from the outside regions. The mean free path length of the neutrals for charge exchange collisions with the argon ions in the core is about 1 cm ($n_n = 10^{14}$ part/cm$^3$; $\sigma_{chx} = 10^{-14}$ cm$^2$); thus about half of the incoming neutral particles collide with ions. The incoming flux of cold neutral particles ($T_n = 300^0$ K; $n_n = 2 \times 10^{13}$ part/cm$^3$) is about $1/4$ $n_n$ $V_{nth} = 2 \times 10^{17}$ part/s cm$^2$. Thus the charge exchange collision time for an ion is about $10^{-3}$ sec. During this time an ion travels about 60 cm in the direction of the anode which corresponds to the e-folding length of the ion temperature in axial direction (eq 2).

The role of the neutral particles in the outside regions ($r > 4$ cm) where the plasma is only weakly ionized, is discussed in section 9.

7. THE ELECTRON TEMPERATURE

Though a good try was made, the electron temperature in the core region of the arc is still not known with the desired precision. The data which may be derived from the Thomson-scattering measurements seem to show that $T_e$ is about equal to $T_i$ or somewhat larger. Similar measurements made before by Gerry and Rose (Lit. 8) yielded $T_e = 4$ to 6 eV. The hollow cathode discharge they used was, however, operated at much lower values of B, I and d and the data cannot be compared directly.

Langmuir Probe measurements made outside the core region yielded $T_e$ values between 1 and 2 eV.

The results may be summarized:

$$T_i < T_e < 2 T_i \quad \text{in the core region} \quad (13a)$$

$$1 \text{ eV} < T_e < 2 \text{ eV} \quad r > 2 \text{ cm} \quad (13b)$$

In contrast to $T_i$ which remains constant up to $r = 4$ cm, $T_e$ drops sharply with radius outside the core region.
8. LOW FREQUENCY OSCILLATIONS (D.J. Kleijn)

8.1. Diagnostics

Low frequency oscillations \((\omega \ll \omega_{ci})\) have been found in the electric potential, the ion density and the electron density. Several diagnostics tools were used for these measurements:

- Electric probes to measure the fluctuations in the floating potential, the ion saturation current and the electron saturation current in the region outside the core of the arc. For constant temperatures the fluctuations in the saturation currents are proportional to fluctuations in the corresponding densities. The spectrum of the probe signals is usually analysed by calculating power spectral density functions from correlation functions. Using two probes located at different positions in the arc the propagation of the waves can be measured from the phase shift in the frequency peaks in the cross-power spectral density function of the two signals.

- A monochromator together with a photomultiplier tube to measure the fluctuations in the intensity of the spectral lines emitted by the plasma. The peaks in the power spectral density function of these signals correspond exactly to those of electric probe signals, which means that the oscillations which are found in the plasma region outside the core, are also present in the core itself.

- High-speed photography to registrate wave motions of the arc as a whole. Streak pictures of a small slit of the arc perpendicular to its axis are useful for measuring frequency and relative amplitude of the oscillations, especially for the so-called \(m = 1\) mode (see section 8.6).

8.2. Description of the electric probes

The probe mountings are the same as used before (lit. 2, Fig. 9). The probe itself has been improved in order to fulfill two requirements:

- the probe may not disturb the plasma-flow
- the probe tip has to be so small and the insulating and shielding so good, that potentials and currents are measured as locally as possible.

To meet these goals a probe has been constructed consisting of a thin conducting pin of tungsten \((\varnothing = 1\,\text{mm})\) surrounded by a ceramic insulator \((\varnothing = 1,5\,\text{mm})\), a shield of stainless steel \((\varnothing = 2\,\text{mm})\), and another ceramic
insulator ($\phi = 4$ mm). The purpose of the conducting shield is to prevent any capacitive coupling of potential fluctuations along the insulated part of the probe to the inner conductor. This shield is electrically connected to the corresponding section of the vacuum-vessel, which is grounded over a large capacitor. The outer insulator prevents short-circuiting of the plasma along the length of the probe. The inner insulator and the conducting shield are respectively 6 and 5 mm shorter that the outer insulator to prevent the forming of a short-circuiting layer of evaporated cathode material (tantalum) between the conducting shield and the inner conductor. The probe is about 10 cm long, the probe tip is 1 mm long and 1 mm in diameter.

The probe is not optimized in an electrical sense, which means that the characteristic impedances of the probe, the probe mountings and the connecting cables are not the same. This might lead to reflections at the interfaces and standing waves that might distort the signals. Calculations and measurements however show that the power spectral density function of a signal is not distorted by the circuit for frequencies below 100 kHz and that a phase shift by the circuit will not take place for frequencies below 300 kHz. The measured frequencies of the oscillations are in practice below 30 kHz. Measurements with two probes on the same axial but different azimuthal positions showed no influence on the signals of one probe by the presence of the second probe.

Fig. 6 shows the probe characteristic for different values of radial position. For both positive and negative voltages a saturation current is found.

8.3. Measurement of power-spectra using correlation functions

The cross-power spectral density function $S_{xy}(\omega)$ of two signals $x(t)$ and $y(t)$ is defined as (see e.g. Lit.9).

$$<x(t)\cdot y(t)> = \int_{-\infty}^{\infty} S_{xy}(\omega) d\omega$$

where the brackets $<>$ mean averaging. $S_{xy}(\omega)$ is related to the Fourier transforms of the two signals according to Parcevals theorem:

$$S_{xy}(\omega) = \lim_{T \to \infty} \frac{X_T(-\omega)Y_T(\omega)}{T}$$

with $X_T(\omega) = \int_{T}^{0} x(t)e^{-j\omega t} dt$
The cross-power spectral density function can be written as the Fourier transform of the cross-correlation function $\psi_{xy}(\tau) = \langle x(t) \cdot y(t + \tau) \rangle$ of the signals according to the Wiener-Khintchine theorem:

$$S_{xy}(\omega) = \int_{-\infty}^{\infty} \psi_{xy}(\tau) e^{-j\omega \tau} d\tau \quad (17)$$

The cross-correlation function of two sinusoidal signals $x(t) = A_x \cos(\omega t + \phi_x)$ and $y(t) = A_y \cos(\omega_0 t + \phi_y)$ equals:

$$\psi_{xy}(\tau) = A_x A_y \cos(\omega_0 \tau + \phi_y - \phi_x) \quad (18)$$

which leads to:

$$S_{xy}(\omega) = \pi A_x A_y \left[ \delta(\omega - \omega_0) e^{j(\phi_y - \phi_x)} + \delta(\omega + \omega_0) e^{-j(\phi_y - \phi_x)} \right] \quad (19)$$

In practice the correlation function of the AC-part of probe signals is measured using a HP-3721-A digital correlator, which calculates the cross-correlation function for 100 positive and 100 negative equidistant values of $\tau$. This function is automatically fed into a HP-3720-A spectrum-analyzer that calculates the real and the imaginary part of the cross-power spectral density function for positive values of $\omega$ according to:

$$S_{xy}(\omega) = \int_{-100 \Delta \tau}^{100 \Delta \tau} \psi_{xy}(\tau) [\cos \omega \tau + j \sin \omega \tau] d\tau \quad (20)$$

where $\Delta \tau$ is the time shift between successive points of the correlation function. For the cross-correlation function of two sinusoidal signals this formula yields:

$$S_{xy}(\omega) = A_x A_y \left[ \frac{\sin 100(\omega + \omega_0)\Delta \tau}{\omega + \omega_0} e^{j(\phi_y - \phi_x)} + \frac{\sin 100(\omega - \omega_0)\Delta \tau}{\omega - \omega_0} e^{-j(\phi_y - \phi_x)} \right] \quad (21)$$

which means that the spectrum of a purely sinusoidal signal has as a consequence of the measuring method a sharp peak at $\omega = \omega_0$ with height $A_x A_y \cdot 100\Delta \tau (V^2/Hz)$ and finite bandwidth $\Delta f = \frac{1}{100 \Delta \tau} (Hz)$.

For stationary signals the autocorrelation function of one signal $\psi_{xx}(\tau) = \langle x(t) \cdot x(t + \tau) \rangle$ is an even function of $\tau$, which means that the power spectral density function of one signal is purely real:

$$S_{xx}(\omega) = 2 \int_{0}^{\infty} \psi_{xx}(\tau) \cos \omega \tau d\tau = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x^2(\omega) d\tau \quad (22)$$
8.4. Frequency measurements

The probe measurements of the oscillation frequencies have been made under a large variety of operating conditions of the arc. Parameters that can be varied externally are the magnetic field strength $B$, the gas feed $Q$, the arc current $I$ and the arc length $L$. By varying the probe position the frequency can be measured as a function of radial and axial positions. The measurements showed that the frequency is constant everywhere outside the core. Combining this fact with the results of measurements of the fluctuations in the intensity of spectral lines, which are emitted essentially by the core leads to the conclusion that the whole arc, including the core region is oscillating with the same frequency. The frequencies of oscillations in the floating potential, the ion saturation current and the electron saturation current exactly coincide.

Frequency measurements have been carried out for all possible combinations of five values of $B$ (1700 G, 2550 G, 3400 G, 4250 G, 5100 G), four values of $Q$ (0.5 cm$^3$/s, 2 cm$^3$/s, 4 cm$^3$/s, 8 cm$^3$/s) three values of $I$ (22.5 A, 45 A, 90 A) and three values of $L$ (60 cm, 140 cm, 210 cm). A number of characteristic results is presented in this section. In most measurements the power spectral density function contained only one discrete frequency peak; in a few cases also higher harmonics were found (Fig. 24).

Fig. 25 shows the oscillation frequency as a function of $B$ for different arc lengths. The measurement at $L = 210$ cm was repeated many times over several days, which gives an impression of the statistical error (error bars in the figure). The measurements show a rather weak dependence of the oscillation frequency on the magnetic field strength.

Fig. 26 shows the influence of the arc length on the frequency, which becomes strong for short lengths. Variation of $Q$ and/or $I$ has no significant influence on the shape of the curves, only on the level.

The Fig. 27 and 28 show the influence of the arc current and the gas feed, which are also stronger than that of the magnetic field strength. Especially for decreasing values of $Q$ the frequency rises very rapidly. Here variation of $B$ and/or $L$ has no significant influence on the shape of the curves.
For some extreme conditions the oscillations disappear. This was especially the case for a long arc \((L = 210 \text{ cm})\) with high arc current \((I = 90 \text{ A})\), low gas feed \((Q < 2 \text{ cm}^3/\text{s})\) and low magnetic field strength \((B = 1700 \text{ G})\), and for a short arc \((L = 60 \text{ cm})\) with low gas feed \((Q = 0.5 \text{ cm}^3/\text{s})\). In the last case a weak oscillation was found at a low arc current \((I = 22.5 \text{ A})\) and a high magnetic field strength \((B > 3400 \text{ G})\) in the range of 90-120 kHz which is about equal to the ion cyclotron frequency.

8.5. **Amplitude measurements**

The amplitude of the oscillations turned out to be strongly radial dependent. From the experiments it became evident that there is a distinct relation between the radial amplitude profiles and the stationary density profiles. From previous measurements we know that these profiles change with arc conditions; so it does not make sense to measure the amplitudes as a function of conditions at one fixed position. Fig. 29 shows the stationary floating potential and the amplitude of the floating potential oscillation as a function of radius; Fig. 30 shows the profiles of the stationary saturation currents together with the amplitudes of the fluctuation in these currents. All probe measurements have been made relatively to the anode, which was grounded for that purpose. From the last figures we see that the modulus of the gradient of the stationary density profiles has two local minima and a local maximum in between, the more inward ones corresponding to minima and maxima in the amplitude profiles. Under different arc conditions profiles of the same characteristics were found; for instance a decrease of the magnetic field gives a broadening of the stationary density profiles and an outward shift of the minima and maxima. When the length of the arc is decreased the more inward kinks in the stationary density profiles become less pronounced and are of smaller scales. All the amplitude profiles rise very rapidly with decreasing radius near the core region, which might be an indication that the instability is actually generated in the core.

As mentioned in the previous section sometimes higher harmonics are found; this is especially the case around the minima in the amplitude profiles.
8.6. Phase Measurements

For correct interpretation of phase measurements one has to know all the impedances in the circuit, especially the impedance of the space charge sheath between the free streaming plasma and the probe surface. Preliminary measurements with a variable Ohmic load gave the impression that this impedance is essentially Ohmic in case of the saturation currents, but that it has a capacitive component for the floating potential. Fig. 30 shows the radial dependence of the phase shift in the oscillation of the floating potential, when two probes are placed under an azimuthal angle of 90° relative to the centre of the arc on the same axial position with one probe on a fixed radial position, while the radial position of the second probe is varied. The load formed by the measuring equipment of both channels is essentially capacitive (700 pF). When the oscillation in the floating potential is described by:

\[ \phi = \phi(r,z) \exp(j(\omega t + m\theta + \phi(r))) \]

we see that the phase shift between the probes \( P_A \) and \( P_B \) positioned at the same radius is:

\[ m(\theta_A - \theta_B) = \phi_A - \phi_B = -90^\circ \]

So \( m = 1 \) and the wave is azimuthally propagating in the direction of the Larmor-precession of the electrons. Adding 90° to the curve in Fig. 30 yields \( \phi(r) = 3,3 \text{ cm} \). Thus we find a phase-lag of points on a smaller radius relative to points on a larger radius. Measurements of the impedance of the space charge sheath have to be carried out to answer the question if the radial phase difference in the floating potential is caused by a radial phase dependence on the real plasma potential or merely by a radial phase dependence on the sheath impedance.

Measurements with two probes on the same radial and azimuthal, but different axial positions (distance between the probes 66 cm) showed no axial phase-shift in the oscillation of the floating potential.
9. DISCUSSION

The experimental findings mentioned in the preceding sections may be compared with the equations of the "two fluid theory" for conservation of particles, momentum and energy (see e.g. Lit.10 and 11). The analysis in this section refers only to the positive column of the discharge (section I). The core region is considered as a linear plasma source, from where plasma particles diffuse into the regular region.

It turns out that the relationship between the experimentally determined d.c. values of $E$, $n_e$, $T_i$, $T_e$, $v$ and $B_z$ is properly described by the momentum equations of ions and electrons. Collisions between ions and electrons in the oppositely directed diamagnetic currents lead to a particle flux in radial direction $n_e v_r$. This flux, together with the particle flux in axial direction $n_e v_z$, enters into the particle conservation equation. The plasma parameters vary both in radial and axial direction. The circumstance that the axial variation of $n_e v_z$ is not known prevents us from checking the particle conservation with the same accuracy as the equation of motion. A problem of particular interest in this connection is the determination of the perpendicular diffusion coefficient of the plasma particles. It can only be concluded that it can be at most two times larger than the "classically" calculated value.

In the core region ionization and recombination phenomena may be of importance; the cross sections for these processes are not known with sufficient precision to make an accurate calculation of the particle balance in this region. Questions concerning the energy balance seem to be the most difficult ones and are not treated yet. An interesting problem in this connection is the constancy with radius of the ion temperature.

At this moment it is not clear whether the low frequency oscillations (section 8) may also be described with the two fluid theory or whether a more complicated kinetic description is required which takes the "finiteness" of the ion Larmor radii into consideration. In that case the existing theory of Rosenbluth and Simon (Lit. 12) should be extended for situations where the axial variation of the plasma parameters is of the same importance as the F.L.R. effects.
9.1. Radial density profile, $n_e(r)$

The radial density distribution of a stationary collisionless plasma of cylindrical geometry with an axial magnetic field present, is expected to be:

$$n(r) = n(0) \frac{\cosh^2 K_2}{\cosh^2(K_1 r^2 + K_2)}$$  \hspace{1cm} (23)

$$K_1 = \frac{eB (\Omega_i - \Omega_e)}{c} \frac{4K}{\left( T_i + T_e \right)}$$

where $\Omega_i(\Omega_e)$ is the angular velocity of the ions (electrons).

$K_2$ is constant which $\rightarrow 0$ for $\beta = \frac{n_e kT}{8\pi B^2} \rightarrow 0$.

This equation follows from the Vlasov equation under assumption of LTE of ions and of electrons (Lit. 13). For the plasma under consideration $\beta = 10^{-2}$ and:

$$n(r) = n(0)e^{-2K_1 r^2}$$  \hspace{1cm} (23a)

This agrees with the experimentally determined distribution (eq. 5) if:

$$q^2 = \frac{1}{2K_1} = \frac{2cK (T_i + T_e)}{eB (\Omega_i - \Omega_e)}$$  \hspace{1cm} (24)

The difference in angular velocity of the ions and electrons is practically equal to the difference of their diamagnetic velocities. According to eq.(1) and eq.(13b) $T_i/T_e$ is constant with radius for $r > 2$ cm, and

$$q^2 = \frac{2cK T_i}{eB \Omega_{Di}} \quad r > 2 \text{ cm}$$  \hspace{1cm} (24a)

Reversely it follows that:

$$\Omega_{Di} = \frac{2cK T_i}{eB q^2}$$  \hspace{1cm} (25)

*) Equation (24a) follows also simply from the expression for the diamagnetic ion current: $\frac{n_e c}{\Omega_{Di}} r B = \frac{\Omega}{\Omega_{Di}} (nkT_i)$. 
which with \( kT_i = \frac{1}{2} m_i v_{it}^2 \) (1) and \( v_{it}(1) = \omega_{ci} v_i \) may also be written as:

\[
\Omega_{Di} = \frac{r_{ci} v_{it}(1)}{q^2} \tag{25a}
\]

Like \( T_i \), \( \Omega_{Di} \) is independent of radius.

In a complete, self consistent theory of the plasma column \( q^2 \) should be calculated from the diffusion equation, but this was not done yet because of the difficulties mentioned before. The experiments indicate that \( q^2 \propto B^{-1} T_i^{-\frac{1}{2}} \) and depends only weakly on the ion mass (only a factor 2.2 difference between argon and hydrogen).

9.2. **Equation of motion of the ions**

In order to understand the behaviour of a plasma in a magnetic field, it is always helpful to keep in mind the behaviour of an individual particle. For this reason the fluid equations may be reduced to single particle equations simply by dividing both sides of the fluid equations by the plasma density. The forces on the particle due to the diamagnetic current and to friction originate from the plasma as a whole, but may be thought of as acting on a single particle. The first object is to describe the equilibrium of the forces which act on a single particle.

The mass motion of the plasma is represented by the velocity of the ion fluid, which may be measured spectroscopically. According to eq.(1) \( \partial T_i / \partial r = 0 \) and the radial part of the equation of motion of the ions may be written as:

\[
-\frac{m_i v_{i\theta}^2}{r} = eE - T_i \frac{1}{n_i} \frac{\partial n_i}{\partial r} - \frac{e}{c} B v_{i\phi} - \frac{m_i v_i r}{r_i} \tag{26}
\]

The last term representing the friction forces on the ions may be neglected if \( \omega_{ci} r_i >> 1 \). The centrifugal force on the left hand side is only of importance for small values of \( r \). For high enough values of \( B \) and \( r \) these terms may be neglected and

\[
\Omega = \Omega_i = \Omega_E + \Omega_{Di} \quad (r > 2 \text{ cm}; \ B > 3000 \text{ G}) \tag{27}
\]

(The direction of the diamagnetic ion current is taken positive). This simple relation describes the rotational motion of a plasma in a magnetic field (see also Lit. 14).
As all quantities in eq.(27) are measured as function of \( r \) it may be checked directly. Fig. 32 shows that for \( B = 3400 \) Gauss it is valid in the region \( 2 \text{ cm} < r < 5 \text{ cm} \). In the region \( r < 2 \text{ cm} \) where the centrifugal force is expected to be of importance, \( E_r \) and \( \frac{1}{n_i} \frac{\partial n_i}{\partial r} \) could not be measured. For \( r > 5 \text{ cm} \) the plasma becomes turbulent. Similar results were obtained for other values of \( B > 3000 \) Gauss.

When \( \omega c_i \tau_i < 1 \) collisions have to be taken into consideration and an expression for \( v_{ir} \) is needed. The simplest one may think of is:

\[
\frac{v_{ir} v_{i\theta}}{r} = \frac{eB}{c} v_{ir} - \frac{n_i v_{i\theta}}{\tau_i} \tag{28}
\]

which reduces for \( \Omega << \omega c_i \) to:

\[
v_{ir} = \left( \frac{1}{\omega c_i \tau_i} \right) v_{i\theta} \tag{28a}
\]

Using eq.(28) to eliminate \( v_{ir} \) in eq.(26) leads to a cubic equation, which may be used to explain the dependence of \( \Omega \) on \( B \) (Lit. 15). For \( \Omega << \omega c_i \) this equation reduces to:

\[
\Omega = \frac{\Omega_E + \Omega_{Di}}{\left(1 + \frac{1}{(\omega c_i \tau_i)^2}\right) + \frac{\Omega}{\omega c_i}} \tag{29}
\]

For low \( B \) values \( \omega c_i \tau_i \to 0 \) and \( \Omega \to 0 \). At values of \( B \) where \( \omega c_i \tau_i \approx 1 \) a flat maximum is reached. (Both \( \Omega_E \) and \( \Omega_{Di} \) are approximately inversely proportional to \( B \) so that eq.(29) has the form \( x^3 + x^2 \) in \( B \).)

In the core of the arc ion-neutral collisions are much less frequent \((10^{-4} \text{s} < \tau_{\text{Chx}} < 10^{-3} \text{s})\) than ion-ion collisions \((\tau_{i,i} \approx 10^{-6} \text{s})\) and \( \omega c_i \tau_i,i \neq 1 \). For the calculation of \( \Omega_E \) and \( \Omega_{Di} \) the values of \( E \) and \( q^2 \) are required, which are not known in the core. Thus formula (29) cannot be checked directly in this region, but it describes properly the shape of the \( \Omega(B) \) curve (Fig.19).

In the regular region \( \omega c_i \tau_i,i \gg 1 \), but ion-neutral collisions may become of importance. Aldridge and Keen (Lit.16) have shown that values found for \( \tau_{\text{Chx}} \) by fitting equation (29) to the experimentally determined \( \Omega(B) \) curve are in good agreement with measurements of Wobschall et al (Lit.17).
The same holds in our parameter regime with higher values of B. The cross section for charge exchange in argon is found to be $\sigma_{\text{Chx}} \approx 10^{-14}$ cm$^2$, a factor 2 to 3 higher than mentioned elsewhere in the literature (see e.g. Lit. 18). This value was also used for the calculations in section 6.2.

The total angular momentum per unit length, $L$, is given by

$$L = 2\pi \int_0^L n_1 m_1 \Omega r^2 dr + L_T$$

where $L_T$ is an eventual small contribution of the turbulent region.

The diamagnetic part is easily found from eq.(1) and eq.(25a). For $B = 3400$ Gauss, $q^2 \approx 6.4$ cm$^2$ and:

$$L_D \approx \pi n_e(0) m_1 q^2 r \cdot v$$

Fig. 32 and similar curves found for other values of B indicate that $\Omega_E$ may also be approximated by a Gaussian function: $\Omega_E \approx \Omega_E(0)e^{-p^2/p^2}$. For $B = 3400$ Gauss, $p^2 \approx 4.5$ cm$^2$ and $\Omega_E(0) \approx 3 \times 10^5$ rad/s. Thus the contribution of the electric drift is:

$$L_E \approx -\pi n_e(0) m_1 p^2 q^2$$

It turns out that within the accuracy of the measurements the total angular momentum of the plasma vanishes! The same was also found for other values of B.

In concluding this section it may be worthwhile to draw the attention to the radial electric field $E_r$. Apparently it is of great importance for the plasma rotation as $\Omega_E$ is comparable and even larger than $\Omega_{Di}$. Whereas the origin of $\Omega_{Di}$ is well understood (see preceding section), $E_r$ has not yet been calculated quantitatively (see section 9.3). The corresponding space charge is given by

$$4\pi \rho = \frac{B}{C} \text{rot } \Omega_E e$$

and is shown in Fig. 13.
In axial direction the equation of motion of the ions reads:

$$0 = -\frac{1}{n_i} \frac{\partial p_i}{\partial z} + eE_z - \frac{m_i}{\tau_{i,e}} \frac{(v_{ez} - v_{iz})}{\tau_{i,e}}$$  \hspace{1cm} (34)

According to eq.(1) and eq.(6) the term $\frac{1}{n_i} \frac{\partial p_i}{\partial z}$ is about $0.16$ eV/cm and points in the direction of the anode. In the core of the arc $E_z$ is about as large and oppositely directed (section 4.3). $v_{ez} \approx 1.5 \times 10^6$ cm/s and $v_{iz} \approx 6 \times 10^4$ cm/s are in the same direction; clearly $v_{ez} \gg v_{iz}$. For the friction force we find about the same value as for the other terms in eq.(34). Agreement better than a factor two cannot be expected for various reasons:

1) the theoretical value of $\tau_{i,e}$ is not known more precisely and its dependence is neglected and  
2) $E_z$ and $v_{ez}$ are measured indirectly with this precision.

A similar equation as eq.(34) holds for the electrons, with the electric force and the friction force pointing oppositely. The fact that $\partial T_e/\partial z \neq 0$ brings an extra term into the discussion of section 4.3. The same which is stated about the accuracy by which the quantities in eq.(34) are known, holds for the corresponding equation for the electrons and the electrical conductivity which is derived from it.

In the regular region the collision term may be neglected. For the ions $(\partial p_i/\partial z)/n_i$ is about the same as in the core region and $E_z$ must be smaller. For the electrons $(\partial p_e/\partial z)/n_e$ is much smaller than in the core region.

In an exact treatment of the particle balance the $z$ dependence of all the plasma parameters in eq.(34) should be known; This is not the case at this moment.

9.3. Particle conservation and diffusion

As mentioned before the plasma particles which are produced in the cathode region move with a velocity of about $6 \times 10^4$ cm/s in the direction of the anode where they recombine. Consequently they stay in the positive column for a time $\tau_i \approx 2 \times 10^{-3}$ s. The question is whether the radial diffusion of the plasma may manifest itself during this time. A direct
affirmative answer to this question is given by the appearance of the core of the arc. In the direction of the anode it becomes more diffuse, its radius increases and its luminosity decreases. Under standard conditions $\Delta r = 2 \text{ mm per m arc length} (\Delta r$ decreases with $B$). This yields at the edge of the core a lower limit $v_r > 2 \times 10^2 \text{ cm/s}$.

The average confinement time $\bar{\tau}_{\text{conf}}$ of the particles may be estimated from the integral conservation law:

$$N_{\text{tot}} = \int_{V_{\text{tot}}} n \, dV = Q \bar{\tau}_{\text{conf}} \quad (35)$$

$\bar{\tau}_{\text{conf}}$ would be larger if not all the particles which enter the cathode region were ionized. The volume integral is taken over the plasma of the positive column. Ionization and recombination in this region are neglected (see section 9.4). Under standard conditions ($B = 3400 \text{ Gauss}; Q = 4.5 \text{ cc NTP/s}$, $q^2 = 6.4 \text{ cm}^2$, $r_k = 4.6 \text{ cm}$) $N_{\text{tot}} = 2.5 \times 10^{17}$ particles and $Q = 1.2 \times 10^{20}$ part/cm$^3$ and $\bar{\tau}_{\text{conf}} = 2 \times 10^{-3} \text{ s}$. This happens to be the same value as found for $\tau_H$.

As $1/\bar{\tau}_{\text{conf}} = 1/\tau_H + 1/\tau_\perp$ it may be concluded within the accuracy of this estimate that $\tau_\perp > 2 \times 10^{-3} \text{ s}$. With the "classical" perpendicular diffusion coefficient $D_{\perp \text{(class)}} = \frac{3 \times 10^{-4} \alpha e}{B^2 T_e}$ one finds

$$\tau_\perp \approx \frac{r^2}{(2.4)^2 D_{\perp \text{(class)}}} \approx 2.5 \times 10^{-3} \text{s} \quad \text{and} \quad v_r \approx \frac{2r}{q^2 D_{\perp \text{(class)}}} \approx 3 \times 10^2 \text{ cm/s} (r \approx 0.7 \text{ cm}).$$

"Drain" diffusion with $D_{\perp \text{(drain)}} = \frac{10^8 T_e}{16 \text{ B}^2} \approx 8 \times 10^3 \text{ cm}^2/\text{s}$ would lead to five times smaller values of $\tau_\perp$ which is very improbable in view of the lower limit for $\tau_\perp$ found above.

In conclusion it may be stated that there are strong indications that the perpendicular diffusion time, $\tau_\perp$, is determined by "classical" diffusion.

A quantitative treatment must start from the particle conservation equation, which reads in the stationary state:

$$\text{div} (n_{\perp} v_{\perp}) = \beta_{\perp} n_{\perp} - \alpha n_{\perp}^2 \quad (36)$$

where $\alpha$ is the recombination coefficient and $\beta_{\perp} n_{\perp}$ the rate of production of charged particles.
9.3.1. Diffusion equation (regular region)

In the regular region the particle diffusion predominates and the right hand side of eq. (36) may be neglected. By introducing the expressions for $v_{ir}$ and $v_{iz}$ the diffusion equation is obtained. The particle current in radial direction, $v_{ir}$, is found by elimination of $v_{i0}$ in eq. (26) with the aid of eq. (28a):

$$v_{ir} = \left( \frac{\omega_{ci} - \Omega}{\omega_{ci}} \right) (\omega_{ci} \tau_i)^2 + 1 = \frac{\mu_i E_r}{D_i} \frac{1}{n_i} \frac{\partial n_i}{\partial r}$$

(37)

Only near the core region $\Omega$ is of some importance; at larger radii it may be neglected in eq. (37). Knowledge of the radial electric field is of crucial importance for a proper understanding of the radial diffusion and related to the question what value of $E_r$ should be used, is the question: what kind of collisions determine $\tau_i$.

According to Simon (Lit. 19, see also Lit. 10) ion-ion collisions would lead to a radial ion velocity (derived from non-diagonal terms of the pressure tensor):

$$v_{ir} = \frac{3}{8} \frac{r_{ci}^4}{\tau_{i,i}} \frac{\partial}{\partial r} \left( \frac{1}{n^2} \frac{\partial^2 n}{\partial r^2} \right)$$

(38)

For a Gaussian density profile (eq. 5)

$$v_{ir} = \frac{3}{\tau_{i,i}} \frac{r_{ci}^4}{q}$$

(38a)

which leads to $v_{ir}$ values of at least one order of magnitude higher than possibly could occur in the plasma under discussion.

Such a fast diffusion of the ions would only be possible if the accompanying space charge field would be "short circuited" by the electrons, thus $E_r = 0$ (Lit. 20). This again is in flagrant contradiction with the experimental evidence - large rotational velocities due to radial electric fields are found even in the direct neighbourhood of conducting end plates. Such a diffusion would also lead to very high radial currents (Lit. 21) which were never found.
Simon's short circuiting mechanism is often used rashly to "explain" anomalies in systems of finite length without its consequences such as mentioned above are taken into consideration, let alone measured. Its physical mechanism is mysterious and never investigated in detail.

Kaufman pointed out that in a system where charge separation takes place the resultant electric field attains such a value as to effectively destroy the flux caused by ion-ion collisions (Lit.22). The right hand side of eq.(37) vanishes because of the ion-ion collisions and for $\tau_i$ should be taken the ion-electron collision time. The diffusion is ambipolar:

$$v_{ir} = v_{er} = \frac{D_{ei}}{(\omega_{ce} \tau_e)^2} \frac{1}{n_e} \frac{\partial n_i}{\partial r}$$

(39)

and according to Kaufman the radial electric field is:

$$E_r = \frac{kT_i}{e} \frac{1}{n_i} \frac{\partial n_i}{\partial r}$$

(40)

The angular velocity would be zero: $\Omega = \Omega_{Di} + \Omega_E = 0$ and for a Gaussian density profile $E_r$ would increase linearly with radius. This radial electric field has the right direction (pointing inward so as to "confine" the ions), but near the core the observed field is four times larger than predicted with eq.(40) and it decreases with radius in the regular region; correspondingly $\Omega \neq 0$. (Fig.17).

The origin of this discrepancy may have to do with the fact that the electron temperature, $T_e$, varies strongly in a region adjacent to the core (eq.13)). The radial particle diffusion is caused by the friction between the oppositely directed diamagnetic currents of the ions and of the electrons. In the core region where $T_e > T_i$, $\Omega_{De} > \Omega_{Di}$; in the region adjacent to the core region, where $\partial T_e/\partial r$ is large, $\Omega_{De} >> \Omega_{Di}$ and in the regular region, where $T_e < T_i$, $\Omega_{De} < \Omega_{Di}$. It is expected that under this condition the particle diffusion increases, but it may be that this extra diffusion is countered by an extra strong radial electric field which holds the ions back.

Another possible explanation may be sought in the finiteness of the ion Larmor radii. Its average value is about 0.5 cm (standard conditions),
but fast ions in the tail of the Maxwell distribution may emerge much further from the core.

Even if the problems around the gradient in the electron temperature and the radial electric field are disregarded and a simple "classical" diffusion mechanism is taken into view, the diffusion equation is difficult to solve. Theoretical calculations of the radial diffusion and its influence on the plasma density profile are complicated by the fact that the perpendicular diffusion coefficient, $D_\perp$, is proportional to $n_e/B^2$ and is thus reversely determined by the density distribution. E.g. with increasing magnetic field strength, $B$, the density in the centre of the arc increases. At the same time the density profile steepens $-1/q^2 \propto B$ and Fick's law $nv_\perp = -D_\perp \frac{\partial n}{\partial r}$ indicates that the radial particle current $v_\perp$ decreases only weakly with $B$ in agreement with the experimental findings.

For a cylindrical plasma column with a Gaussian distribution according to eq.(5) the radial contribution to the particle conservation equation is:

$$\frac{1}{r} \frac{\partial}{\partial r} (r n \nu_\perp r) = (\frac{\Delta}{q^2} - \frac{8 \pi^2}{q^4}) D_\perp n_\perp$$

(41)

This indicates that close to the core ($r < \sqrt{q/2}$) particles must flow in along the axis and further away from the core particle must flow out. In the absence of ionization and recombination the axial contribution to the diffusion equation must be equal to the radial contribution. The approximate relationship between the parallel diffusion coefficient, $D_\parallel$, and the perpendicular diffusion coefficient, $D_\perp$, is $D_\parallel = L^2/4r_0^2 D_\perp$ which yields $D_\parallel \approx 5 \times 10^5 \text{ cm}^2/\text{s}$. The order of magnitude of the contribution to the axial velocity of the particles due to diffusion must be $v_\parallel (\text{diff}) \approx 2D_\parallel/L \approx 10^4 \text{ cm/s}$. As mentioned before spectroscopical and Langmuir probe measurements indicate an axial velocity $v_z = (6 \pm 2) \times 10^4 \text{ cm/s}$. In order to obtain direct information about $v_\parallel (\text{diff})$ the axial velocity should be measured with an accuracy of better than 5%, which is outside the realm of the present possibilities.

It may be attempted to calculate $v_{\perp z}$ theoretically by eliminating $E_z$ from eq.(34) and its counterpart for the electrons. For radii larger than $r \approx 2 \text{ cm}$, $\partial T_e/\partial z = 0$ whereas $\partial T_i/\partial z \neq 0$. It follows:
\[-(T_i + T_e) \frac{\partial n_e}{\partial z} - n_e \frac{\partial T_i}{\partial z} = \left( \frac{m_i}{\tau_{i,e}} - \frac{m_e}{\tau_{e,i}} \right) (v_{iz} - v_{ez}) \quad (42)\]

No large currents flow in the regular region and \(m_i/\tau_{i,e} = m_e/\tau_{e,i}\), so that the right hand side of eq.(42) is expected to be relatively small and with eq.(13) we find:

\[(2 \text{ to } 3) \frac{1}{n_e} \frac{\partial n_e}{\partial z} = - \frac{1}{T_i} \frac{\partial T_i}{\partial z} \quad (42a)\]

\(\partial T_i/\partial z \approx 60 \text{ cm}\) and a doubling to the density over a distance of 2 m is very well possible (see Fig.9). The right hand side of eq.(42a) is well known, but the left hand side on the contrary is poorly known. From these considerations it is clear that \(v_{iz}\) cannot be determined precisely with the information which we have at hand.

At larger radii friction with neutral particles may become of importance (see Fig.23). In that case \(v_{iz} = v_{ez}\) equals the "ambipolar" speed \(v_a\):

\[v_a = - \frac{D}{a} \frac{1}{n_e} \frac{\partial n_e}{\partial z} \quad (43)\]

where \(D_a\) is the usual ambipolar diffusion coefficient\(^\star\). (see e.g. Lit.23)

9.3.2. Ionization and recombination

The contribution of collisional ionization to the particle conservation equation is \(\beta n_e\), which means that \(1/\beta\) presents an average "ionization time", \(\tau_{ion}\), for the production of a pair of plasma particles. As the axial drift velocity, of the electrons, \(v_{ez}\), amounts to about \(1/40\) of their average thermal velocity, \(v_{et}\), the ionization is not obtained from \(v_{ez}\), but from fast electrons in the tail of the Maxwellian velocity distribution. The ionization rate, \(\beta\), is approximately given by (Appendix 3, Lit. 23):

\(^\star\) A sinusoidal axial density distribution \(n(z) \sim n_0 \sin \frac{nz}{2L}\) as was assumed by Simon (Lit.4) allows a simple solution of the diffusion equation, but it is improbable and was never verified experimentally. In our machine the axial density distribution is certainly not sinusoidal.
where $X_i$ is the ionization potential ($X_i = 15.7$ eV for argon), $p_0$ is the neutral particle pressure and $a$ is a factor which amounts for argon to about 0.7. In the middle of the core ($n_0 = 10^{12}$ part/cm$^3$ and $T_e = 6$ eV) one finds $\beta = 10^3$ s$^{-1}$ and $\tau_{\text{ion}} = 10^{-3}$ s. As this is comparable to $\tau_{\text{conf}}$, $\tau_{\text{uf}}$, and $\tau$, the contribution of ionization may not be neglected, certainly not at the cathode side where $T_e$ is large.

In the regular region the neutral particle density, $n_0$, is larger (Fig.23) and $T_e$ (1 to 2 eV) is smaller than in the core region. The contribution of ionization to the particle balance is less important, but probably not quite negligible. Particularly in the region adjacent to the core the particle production may help to overcome the negative contribution of the radial diffusion.

The contribution of radiative recombination to the particle conservation equation is $\alpha n_0^2$. The recombination coefficient, $\alpha$, is even less well known than the ionization coefficient. Experiments with argon yield values of $\alpha = 10^{-11}$ cm$^3$/s whereas the theoretical values are one or two orders of magnitude smaller (Lit.23). In the core region the "recombination time" for a particle $\tau_{\text{rec}} = \frac{1}{n_0 \alpha} = 10^{-3}$ s $\approx \tau_{\text{ion}}$.

Thus collisional ionization and radiative recombination may balance each other (corona equilibrium). Correspondingly the Corona formula (Lit.24) yields a degree of ionization of about one percent. As $n_e$ drops steeply with radius, recombination is expected to be negligible in the regular region. These are the reasons for neglecting the right hand side of eq.(36) as a first approximation in calculations concerning the particle conservation and diffusion.

9.4. Stability - low frequency oscillations

From the foregoing discussions it may be concluded that the equilibrium of the plasma is not disturbed by a strong instability. Up to $r = r_k$ the plasma loss is within a factor two of what the "classical" theory predicts and an uncertainty of a factor two may also be due to imperfections of the...
theory applied so far (no z dependence, uncertainties in the used cross sections).

At the other hand low frequency oscillations were found everywhere in the plasma. The amplitude of these oscillations is maximum near the core region and is vanishing small in the turbulent region. This indicates that the low frequency oscillations are not responsible for the turbulent behaviour at \( r > r_k \). From Fig.30a and Fig.30b it seems more probable that they are related to the small dents in the -overall- Gaussian radial density profile. In axial direction the amplitude of the oscillations does not vary much, which is an indication that they are not generated in the cathode region, but originate in the plasma of the positive column.

By identifying the low frequency oscillations three important, experimentally established, features have to be taken into consideration:
- The frequency of the waves is constant as a function of space coordinates and \( \omega \ll \omega_{ci} \).
- No phase shift as a function of z was found.
- The waves are azimuthally \( m = 1 \) modes, rotating in the direction of the electrons.

Moreover the dependence of their frequency on the gas discharge parameters \( B, L, I \) and \( Q \) (Fig.27-29) has to be understood.

Two types of instability may be responsible for the low frequency oscillations: the drift instability and the gravitational instability.

**Drift oscillations** are due to the presence of a radial density gradient in the plasma. The phase velocity of these oscillations coincides with the diamagnetic motion of the electrons and their angular frequency is given by (see e.g. Lit.25):

\[
\omega_{\zeta} = \frac{T_e}{m e \omega_{ce}} \frac{\partial \ln n}{\partial r} \quad \zeta
\]

(45)

\( K_\zeta \) is the wave number in azimuthal direction. Its smallest value \( K_\zeta = 1/r \) corresponds to \( \lambda = 2\pi r \) (\( m = 1 \) mode). From eq.(5) it follows that \( (\partial \ln n/\partial r) = 2r/q^2 \), thus:
or in terms of the ion Larmor radius, $r_{ci}$:

$$
\omega^2 = \frac{2T_e}{m_e \omega_{ce} q^2}
$$

(45a)

At the middle of an arc of 140 cm length, $T_e = (6 \pm 2) \text{ eV}$ and $q^2 = 6.4 \text{ cm}^2$ at $B = 3400 \text{ Gauss}$. Eq. (45a) yields $\omega^2 = (6 \pm 2) \times 10^4 \text{ rad/s}$ whereas the experimental value is $\omega = 10^5 \text{ rad/s}$ (Fig. 25). The reason for this discrepancy may be that the electron temperature, $T_e$, is not constant with radius neither with axial distance, $z$. The large values of $\partial T_e / \partial r$ in the region next to the core may cause an increase in the $\omega^2$ value of eq. (45a). The variation of $T_e$ with $z$ would correspond with an axial variation of $\omega^2$, whereas the frequency of the oscillations is found to be the same everywhere in the plasma.

Apart from these important question marks, eq. (45a) gives a proper description of the dependence of $\omega$ on the various plasma parameters.

- $\omega$ is only weakly dependent on $B$ (Fig. 25) in agreement with the finding $q^2 \sim B^{-1}$ (section 3.1).
- $\omega$ increases with $I$ (Fig. 27), like $T_e$ does.
- like $T_e$, $\omega$ increases inversely with $Q$ (Fig. 28) enhanced by the fact that $q^2$ increases with $Q$.
- the dependence of $\omega$ on $L$ may be due to the modification of $\omega^2$ by $k_z v_A$, where $v_A$ is the Alfvén velocity ($v_A = 10^7 \text{ cm/s}$) and $k_z$ is the axial wave number. This causes an increase of $\omega$ at lower values of $L$ (see Fig. 18 of Lit. 25*).

Among the various ways that drift instabilities may manifest themselves, it seems the most probable that we have to do with the drift dissipative instability which becomes dominant when electron collisions are of importance for the particle transport in longitudinal direction, i.e. when $L \gg \lambda_e$.

In our case $L / \lambda_e = 100$ and the additional condition $\omega_{ci} / \tau_i >> 1$ is marginally fulfilled. The dispersion relation reads:

$$
\omega^2_{ci} \tau_i \gg 1
$$

*) The much weaker variation with $B$ is caused by the fact that $n_e$ increases with $B$. The ion sound velocity may be neglected.
\[ w^2 + i \omega_s - i \omega_s \omega^* = 0 \] (46)

where \( \omega_s = (k_z/k_e)^2 (\omega \tau_e \rho_e)^2 \).

\((k_z/k_e)^2 = \frac{r^2}{L^2}, (\omega \tau_e \rho_e) \approx 100 \) and \( \omega_s \) is in the range \( 10^4 - 10^5 \). Eq. (46) is derived under the assumption that \( \rho_e k^2 \) may be neglected compared to \( \omega_s \), a condition which is also marginally fulfilled. As \( \omega_s \sim \omega_s \), the growth rate \( \gamma = \omega \).

In the core region the longitudinal current may also have an effect on \( \gamma \).

Whether these oscillations cause an extra particle transport depends on the phase relation between the oscillating electric potential, \( \Phi \), and the density fluctuations, \( \tilde{n}_e \). As mentioned in section 8 the phase difference between the oscillating floating potential and the ion saturation current was found to be small. This leads to \( \tilde{n}_e \tilde{V}_E = 0 \) where \( \tilde{V}_E \) is the electric drift velocity due to \( \tilde{E}_z \). Therefore, it is not surprising that notwithstanding the presence of strong drift oscillations no anomalous high particle losses were found. Diffusion coefficients which were derived from drift oscillations and attain values as high as \( D_\parallel \) (Bohm) or even larger (Lit.25) are not relevant in this case.

The gravitational or flute instability is expected to have a frequency \( \omega = \sqrt{g}/l \) where the acceleration due to the gravitational force \( g = \Omega^2 r \) and \( l \) is a characteristic length. This leads to:

\[ \omega \approx \sqrt{\frac{g}{l}} \Omega \] (47)

Indeed \( \omega \) is found to be a fraction (about 0.4) of \( \Omega(0) \), but at larger radii \( \Omega \) decreases rapidly and even changes sign (Fig. 17). Furthermore \( \Omega \to 0 \) at the anode region and again the question arises how this is to reconcile with the fact that \( \omega \) has the same value everywhere in the plasma.

The flute instability is strongly modified by the so called Finite Larmor Radii effects as was first pointed out by Rosenbluth, Krall and Rostoker (Lit.26). Stabilization occurs if:

\[ \left( \frac{r}{l} \right) \Omega^2 < \frac{\omega_i^2 \rho_i}{\zeta} \], stable \] (48)

In our case \( (r/l) = 0.16 \). In the core region \( \Omega \approx 2.5 \times 10^5 \) and
$\omega^* = 6 \times 10^4$ and the left hand side of eq. (48) is one order of magnitude larger than the right hand side.

A criterion for the $m = 2$ mode is:

$$-0.2 < \frac{\Omega_E}{\Omega_{Di}} < 1.2 \text{, stable}$$

In the core region where the plasma rotates as a solid body $\Omega_E = -6\Omega_{Di}$, so that the plasma is expected to be unstable. Although these instability criteria are heavily violated, no instability of the plasma is found.

In the regular plasma region the rotation is sheared. This case was treated theoretically by Rognlien (Lit. 27) who started from the work of Rosenbluth and Simon (Lit. 12), assuming a Gaussian density profile up to an outer radial boundary. Identification of this boundary with radius $r_k$ (see Lit. 1 Fig. 10b) makes Rognlien parameters $X_b = r_k^2/q^2 \approx 3.5$ and $p = 2$ for the $m = 1$ mode. For uniform rotation the plasma is expected to be unstable with $\gamma = \omega = \Omega_{Di} = 3.5 \times 10^4 \text{ rad/s}$. The effect of shear was calculated numerically for a velocity profile of the electrical drift of the form $\Omega_E = 2 + s \left(\frac{r}{q} - 1\right)$. Though this profile does not fit well with the measured one, the result of the calculations shows an interesting feature: for values of $s \approx -2$ the plasma is stable.

It has to be noted that all calculations on F.L.R. stabilization of the flute instability assumed the temperatures to be constant in radial and axial direction (infinite cylinder), which is apparently not fulfilled in the plasma under discussion. Rognlien's results happen to be valid if $T_e$ varies radially.
10. APPENDIX - THOMSON SCATTERING MEASUREMENTS (W.F.H. Merck, A.F.C. Sens, A.H.M. van de Ven)

10.1. Introduction

By means of laser light scattering on free electrons it is possible to determine the electron temperature, $T_e$, and the electron density, $n_e$, of a plasma. In order to measure the velocity distribution of the electrons an important condition has to be fulfilled. The parameter $\alpha$, which compares the wavelength, $\lambda_0$, of the incident radiation with the Debye length, $\lambda_D$, has to be much smaller than unity. For $\alpha = \lambda_0/4\pi \lambda_D \sin \theta/2 \ll 1$ the spectrum of the scattered light reflects the electron velocity distribution ($\theta$ is the angle of observation of the scattering with respect to the forward direction of the incident radiation).

In this case the scattering cross-section per unit of space-angle for one electron is (see e.g. Lit. 28):

$$\frac{d\sigma}{d\Omega} = r_0^2 \sin^2 \rho = \left(\frac{e^2}{4\pi \varepsilon_0 m_e c^2}\right)^2 \sin^2 \xi$$

in which $r_0$ is the classical radius of an electron, $\xi$ is the angle of observation with respect to the direction of polarisation of the incident radiation. In our experiment $\xi = 90^0$ and the scattering cross-section is $d\sigma_{90}/d\Omega = 7.95 \times 10^{-26} \text{ cm}^2/\text{ster}$.

If we assume a Maxwellian velocity distribution, the electron temperature can be calculated from:

$$\frac{kT_e}{e} = \frac{m_e c^2}{e} \frac{\left(\frac{\lambda_1}{\lambda_0}\right)^2}{16 \ln 2} = 9.6 \times 10^{-4} \lambda_1^2$$

where $\lambda_0$ is the wave length of the laser light (in our case $\lambda_0 = 6943 \text{ Å}$) and $\lambda_1$ is the halfwidth in Å of the wave length profile.

Theoretically the wave length profile is given by the expression:

$$E_{\text{Th}} (\Delta \lambda) = E_L \frac{d\sigma_{90}}{d\Omega} d\Omega P(\Delta \lambda) n_e$$

where $E_L$ is the total laser energy passing through a surface $S$, $\Delta \lambda = \lambda - \lambda_0$, and

$$P(\Delta \lambda) = \frac{1}{\sqrt{2\pi}(\lambda_1/8\ln 2)} e^{-\frac{(\Delta \lambda)^2}{2 (\lambda_1)^2/8\ln 2}}.$$
The total scattered energy of all free electrons in a volume $S_dz$, with electron density $n_e$, in a solid angle $d\Omega$ is given by:

$$E_{\text{tot}} = \int E_{\text{Th}} (\Delta \lambda) d(\Delta \lambda) = E_L \frac{d\sigma_\text{Th}}{d\Omega} dz d\Omega n_e$$

With an electron density $n_e = 10^{14} \text{ cm}^{-3}$ this energy equals the energy of the Rayleigh-scattering of approx. 1.2 Torr Ar. at $T = 273 \text{ K}.$

If the halfwidth of the monochromator profile $\Delta \lambda'$ is much smaller than the halfwidth of the Thomson-scattered spectrum $\lambda_1$, the amount of electrons arriving at the anode of the photomultiplier, $N_e$, can be calculated from

$$N_e = \frac{\Delta \lambda'}{\Delta \lambda} \cdot T \cdot A_{\text{PM}} \cdot n_{\text{PM}} E_{\text{Th}} (\Delta \lambda)$$

where $T$ is the overall transmission-factor, $A_{\text{PM}}$ is the amplification factor of the photomultiplier and $n_{\text{PM}}$ its quantum efficiency. The photomultiplier signal is $V_{\text{PM}} (\Delta \lambda) = \frac{N_e \epsilon}{\Delta t} R$ where $R$ is the anode impedance and $\Delta t$ is the duration of the laserpuls. In our experiment $V_{\text{PM}} (\Delta \lambda) = E_L P(\Delta \lambda) n_e 35.10^{-23} \text{ V}$. The electron density, $n_e$, follows from:

$$V_{\text{PM}} (0) = E_L n_e \frac{32.8}{\lambda_1} 10^{-23} \text{ V}$$

where $V_{\text{PM}} (0)$ is the peakvalue of the scattered light ($\Delta \lambda = 0$).

10.2. Diagnostic equipment

Fig.33 shows a schematic of the set-up. The equipment is mounted on a frame of aluminum optical rail (Micro-controle) with the optical axis perpendicular to the axis of the plasma-vessel. Radial scanning of the plasma is obtained by moving the frame vertically (range 4 cm). In order to facilitate the optical adjustment it can also be moved in the direction of the optical axis over a distance of 60 cm. A picture is shown in Fig.34.

The scattering experiment is performed with a ruby-laser (wavelength $\lambda_0 = 6943 \text{ A}$) emitting a horizontally polarised laser beam. It produces an energy of 30 Joules in the normal mode ($\Delta t$ is appr. 1.6 ms) and 2 Joules in the Q-switched mode. The laser beam is focussed by means of two lenses ($f_1 = 150 \text{ mm}, f_2 = 500 \text{ mm}$) to a spot of 1.3 mm diameter in the middle of the vessel.

The spectrum of the scattered light is scanned with a 0.25 meter Jarell Ash monochromator (f: 3.5 and a dispersion of 66 Å/mm at the exit slit when
a 590 line grating is used). The grating is blazed at 7500 Å and has an efficiency of 78% at 6950 Å. The slitwidth is 100 µm for both the entrance slit and the exit slit, corresponding to approximately Δλ' ≈ 7 Å. The entrance slit of the monochromator is projected on the radiated spot by means of a lens f = 200 mm and a prism. The magnification factor is 2.5, so that dz = 2.5 x 10^{-2} cm.

In order to reduce the disturbance of wall-scattered light, tubes with limiting diaphragmas are placed in the plasma vessel and accurately adjusted around the incident laser beam. Brewster plates are mounted opposite to the ruby-laser and the detection equipment. The solid angle of observation is determined by a diaphragma of 19 mm diameter placed in the detection tube, at a distance of 222 mm from the focal point. Thus the solid angle of observation, dΩ, is about 5.8 x 10^{-3} sterrad and for a slitwidth of 100 µm, \[ \frac{dΩ}{dΩ} \cdot dzdΩ \approx 11.5 \times 10^{-30} \text{ cm}^3. \]

Along the optical path of the detection an U.V. filter is mounted to prevent that the second order spectrum of lines emitted by the arc in the 3500 Å region reach the photocathode of the photomultiplier. By using a horizontally oriented polarization filter the signal to noise ratio is improved by a factor 2. Behind the exit slit of the monochromator a lens is used in order to receive the total light energy on the photocathode and a heated quartz window has to prevent fogging up when the photomultiplier is cooled. The overall transmission factor of the optical detection path, T_r, is about 25%. (3 windows, 2 lenses, 1 prism, 1 U.V. filter, 1 pol. filter and the monochromator.)

A R.C.A. photomultiplier with GaAs cathode, type C 31034 A is used for detection of the scattered light. The quantum efficiency, n_pM', is about 25% at 7000 Å and the amplification-factor, A_{PM}', is about 4.10^5. The sensitive surface of the photo cathode is 4 x 10^{-2} mm².

In order to bring the dark-current well below 1 nA the photomultiplier, housing is cooled with dry ice. An extra magnetic shielding is necessary to avoid disturbance by the magnetic field. The signal from the photomultiplier is detected by a storage oscilloscope (Tetronix, type 7633). Because the shape of the signal due to Thomson-scattering is not sharply defined an integrator should be used.
10.3. Results

Fig. 35 shows the total scattered light detected under an angle of 90° of laser light which was focussed on a spot in the core of the arc, 24 cm in front of the anode (z = 100 cm). The spectrum of the Thomson scattered light may be found after substraction of the stray scattered light. As the stray scattered light has a relatively high intensity, the Thomson signal in the vicinity of the laser line (Δλ = 10 Å) is measured only inaccurately. In our experiment the stray scattered light was reduced to a level corresponding to the Rayleigh scattering of Argon gas at a pressure of 0.3 Torr (T = 273° K). Further away from the laser line an a.c. component in the radiation emitted by the plasma itself causes large errors in the measurements. The spectrum of the argon radiation made measurements outside the 6900 - 6960 Å region impossible. Improvements may only be obtained by application of more laser power than the 30 Joule used so far*. Following Gerry and Rose (Lit.8), the electron temperature may be obtained by plotting the net Thomson signal versus the electron energy (which is proportional to the square of the wave length shift)-(Fig. 36). Under the conditions mentioned before the electron temperature, T_e, is found between 2 and 3.4 eV (rather low, because z is large). The corresponding electron density is approximately 0.5 x 10^{14} part/cm^3. Similar -rather inaccurate- results were obtained at other axial positions in the arc (Lit.29).

*Q-switching of the laser offers in principal a possibility of improvement, but the total number of detected photons is so low in that case that the statistical noise in their number becomes important.
REFERENCES


\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Fig. 1}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Fig. 1}
\end{figure}
$T_i$ Measured at $Z=0\text{cm}$.

$B = 3400 \text{ G}$.

$I = 100 \text{ A}$.

ERROR.
Fig. 4a

Ti (eV)

Z = 50 cm.
I = 100 A
B = 3400 G
L = 140 cm.

Fig. 4b

(Ti)_0 (eV)

Z = 0 cm.
I = 100 A
B = 3400 G.

Q (cm³ NTP/s)
Fig. 5

$T_i$ (eV)

$Q = 1 \text{cm}^3 \text{NTP/s}$

$Q = 4.5 \text{cm}^3 \text{NTP/s}$

$Z = 50 \text{ cm}$

$I = 100 \text{ A}$

$L = 140 \text{ cm}$

Error
$B = 2550 \text{ G}$
$I = 90 \text{ A}$
$G = 45 \text{ cm}^3 \text{ NTP/s}$
$L = 140 \text{ cm}$
$Z = 50 \text{ cm}$
Gas = Argon.
Fig. 7

Is (mA) vs. r (cm)

B = 1700 G, 3400 G, 5100 G
Ceramic insulation.

Ceramic

Tungsten wire

Copper.

Tungsten wire

Shaft of adjustable probe.

Fig. 8. RING SHAPED PROBE.

Fig. 8a.
ION SATURATION CURRENT TO THE RING-SHAPED PROBE (mA).

Fig. 9

$Z$ (cm)

reg10n 0 10 20 30 40 50 60 70 80 90 100 110 120

$q^2$ (cm$^2$)

$Q$ (cm$^3$ NTP/s)
Fig. 12

\[ V \text{ (Volts.)} \]

\[ Q = 4.5 \text{ cm}^2 \text{NTP/s.} \]
\[ B = 3400 \text{ G.} \]
$E_r \ (\text{V/cm})$

$\rho/e \ (10^6 \text{part/cm}^3)$

$B = 3400 \text{ G}$
$I = 100 \text{ A}$
$Q = 4.5 \text{ cm}^3 \text{ NTP/s}$
$L = 140 \text{ cm}$
$Z = 50 \text{ cm}$

Fig. 13.
Fig. 14
Fig. 15.

B = 3400 G  
I = 100 A  
L = 140 cm.

Fig. 16.

Q (cm³ NTP/s)  
B_z (560 G)
$\Omega \left( 10^5 \text{ rad/s} \right)$

$I = 100 \text{ A}$
$Q = 4.5 \text{ cm}^3 \text{ NTP/s}$
$L = 140 \text{ cm.}$
$Z = 50 \text{ cm.}$
$d = 13 \text{ mm.}$

**Fig. 17** ANGULAR FREQUENCY AS FUNCTION OF RADIUS
\[ \Omega_0 \text{(}\times 10^5 \text{rad/s}) \]

\[ Q = 1 \text{ cm}^3 \text{ NTP/s} \]

\[ Q = 4.5 \text{ cm}^3 \text{ NTP/s} \]

Fig. 18

- B = 3400 G
- L = 140 cm
- Z = 50 cm
- d = 13 mm
Fig. 19

\[ \Omega_0 \left(10^5 \text{rad/s}\right) \]

- \( Q = 1 \text{cm}^3 \text{NTP/s} \)
- \( Q = 45 \text{cm}^3 \text{NTP/s} \)
- \( Z = 50 \text{cm} \)

Fig. 20

\[ B = 3400 \text{ G} \]

\[ \Omega_0 \left(10^5 \text{rad/s}\right) \]

\[ Q \left(\text{cm}^3 \text{NTP/s}\right) \]
Fig. 21

\[ \Omega_0 \left(10^5 \text{ rad/s}\right) \]

\[ d = 20 \text{ mm} \]
\[ B = 3400 \text{ G} \]
\[ Q = 8 \text{ cm}^2 \text{ NTP/s} \]
\[ L = 140 \text{ cm} \]
\[ Z = 50 \text{ cm} \]

\[ \times \Omega_0 \]
\[ \bullet T_i \]

Fig. 22

\[ \Omega_0 \left(10^5 \text{ rad/s}\right) \]

\[ d = 20 \text{ mm} \]
\[ I = 150 \text{ A} \]
\[ B = 3400 \text{ G} \]
\[ Q = 8 \text{ cm}^2 \text{ NTP/s} \]
\[ Z = 50 \text{ cm} \]

\[ \times \Omega_0 \]
\[ \bullet T_i \]
Fig. 23

OUTWARD FLUX OF HOT NEUTRALS.

INWARD FLUX OF COOL NEUTRALS

\( T_n (^\circ \text{K}) \)

\( P_n (10^6 \text{ Torr}) \)

\( n_n (10^{10} \text{ part/cm}^3) \)

\( r (\text{cm}) \)
Fig. 24. X-Y RECORDING OF POWER SPECTRAL DENSITY FUNCTIONS OF THE LOW FREQUENCY OSCILLATIONS WHICH ARE GENERATED SPONTANEOUSLY IN ARGON PLASMA.
Fig. 25

Q = 4 cm$^3$ NTP Argon/s
I = 90 A

f. peak (KHz)

Fig. 26

Q = 4 cm$^3$ NTP Argon/s.
I = 90 A.

f. peak (KHz)
**Fig. 27**

- **B = 3400 G**
- **L = 140 cm.**
- **Gas = Argon.**

Graph showing variation of f. peak (KHz) with I (A) for different values of Q (cm³ NTP/s).

- Q = 0.5 cm³ NTP/s
- Q = 2 cm³ NTP/s
- Q = 4 cm³ NTP/s
- Q = 8 cm³ NTP/s

**Fig. 28**

Graph showing variation of f. peak (KHz) with Q (cm³ NTP/s) for different values of I (A).

- I = 90 A
- I = 45 A
- I = 22.5 A
$V_{\text{floating}} = (\text{volt})$

$V_{\text{floating}} \sim (\text{volt})$

Fig. 29a. RADIAL DEPENDENCE OF DC FLOATING POTENTIAL.

Fig. 29b. RADIAL DEPENDENCE OF AMPLITUDES OF OSCILLATION IN FLOATING POTENTIAL.

B = 3400 G.
Q = 4,5 cm$^3$ NTP/s.
I = 90 A.
L = 210 cm.
Gas: Argon.
Oscillation frequency = 13,5 KHz.
Fig. 30a. RADIAL DEPENDENCE OF DC PROBE SATURATION CURRENTS

Fig. 30b. RADIAL DEPENDENCE OF AMPLITUDE OF OSCILLATION IN THESE CURRENTS.
MEASUREMENT OF AZIMUTHAL AND RADIAL PHASE RELATIONS.

$\theta_B - 90^\circ$
$\theta_A - 0^\circ$

$\psi_{AB}(\tau)$

$S_{AB}(\omega)$

HP 3720 A Spectral Analyser

Fig. 31

$\phi_A - \phi_B$

RADIAL DEPENDENCE OF PHASE SHIFT IN OSCILLATION WITH PROBE PB IN FIXED POSITION AT $r = 3.3$ cm.

$B = 3400$ G
$Q = 4.5$ cm$^3$ NTP/s
$I = 90$ A
$L = 140$ cm.
Gas = Argon.

$r_{probeA}(cm)$
Fig. 32

\[ \tau (10^5 \text{rad/s}) \]

- \( \Omega \) (solid line)
- \( \Omega_E \) (dashed line)

- \( I = 100 \text{ A} \)
- \( Q = 45 \text{ cm}^3 \text{NTP/s} \)
- \( B = 3400 \text{ G} \)
- \( d = 13 \text{ mm} \)
- \( L = 140 \text{ cm} \)
Fig. 33. LASER EQUIPMENT.

RL RUBY LASER
EM ENERGY MONITOR
BP BREWSTER PLATE
P PRISM
M MONOCHROMATOR
PM PHOTOMULTIPLEXER
D1-D3 DIAPHRAGM
F1-F2 FILTER
L1-L4 LENS
T1-T4 TUBE
W1-W3 WINDOW
Fig. 34 THOMSON SCATTERING EQUIPMENT.
$V_{PM} \text{ (mV)}$

- THOMSON SCATTERING
- STRAY SCATTERING
- THOMSON SCATTERING

$Q = 4.5 \text{ cm}^3 \text{NTP/s Ar}$
$Z = 100 \text{ cm.}$

Fig. 35.
Fig. 36

THOMSON SCATTERING

0 = 4.5 cm³ NTP/s Ar
Z = 100 cm

Electron energy (Volts)