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Experiments with a large sized hollow cathode discharge, III

Concluding work January 1975 to June 1976

EURATOM - THE Group "Rotating Plasma"

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EXPERIMENTS WITH A LARGE Sized HOLLOW CATHODE DISCHARGE, III

CONCLUDING WORK JANUARY 1975 TO JUNE 1976

EURATOM - THE Group "Rotating Plasma"
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ABSTRACT

The concluding work of investigations on a large sized hollow cathode discharge is reported in six chapters dealing with miscellaneous subjects. As before the attention is mainly directed towards the positive column.

After a chapter which contains supplements to the 1974 annual report, operation of the arc with other gases than argon is treated. Two chapters are devoted to special ways of operation of the arc, which are of particular interest for potential mass separative properties of the arc. Finally a possible origin of the mass rotation and the energy transport are discussed.

The most salient conclusions are that in the positive column of a hollow cathode discharge
- The relationship between the experimentally determined d.c. values of $n_e$, $T_i$, $v_f$, $E$, and $B$ is properly described by the equation of motion of the ions,
- the electric conductivity is "normal" within a factor two,
- the leak of particles through the magnetic field is within a factor two determined by "classical diffusion",
- the "classical" power balance equation is also well fulfilled by the ions, but the stationary power balance equation of the electrons shows a large surplus,
- the ion temperature is constant with radius, contrary to the electron temperature which drops sharply near the core of the arc,
- the electrons are heavily affected by strong non linear low frequency oscillations which may lead to "drain" of energy in radial direction,
- the strong radial gradient in the electron temperature in combination with the finite Larmor radii of the ions may cause the mass rotation of the plasma,
- though the plasma is highly ionized (> 95%) neutral particles do play an important role in the positive column: e.g. charge exchange collisions are responsible for an axial gradient in the ion temperature.
1. INTRODUCTION

This is the last report of the experiments in plasma physics which were done under a five year contract (1971 - 1975) between Euratom and the TH Eindhoven. One of the main objects of the work was to obtain by means of a large sized hollow cathode discharge (see Fig.1) a better insight in the phenomenon of plasma rotation and to see whether the rotation of the plasma in this discharge may be used for isotape separation. The latter subject is treated in a separate publication.

In the previous annual reports (Lit.1 - 3) the experimentally determined variations of the plasma parameters \( n_e(r,z) \), \( T_i(r,z) \), \( T_e(r,z) \), \( v(r,z) \) and \( \phi(r,z) \) with the gas discharge parameters (arc current \( I \), gas feed \( Q \), magnetic field strength \( B \) and arc length \( L \)) were shown. It turned out that up to a radius \( r = 4.5 \text{ cm} \) the relationship between the d.c. values of \( n_e, T_i, T_e \) and \( B \) is properly described by the equation of motion of the ions and that the radial particle flux is within a factor two determined by "classical diffusion". In Chapter 2 of this report the results of some supplementary measurements (Thomson scattering) were made and \( T_i \) and \( v \) were determined (Doppler broadening and - shift of spectral lines) up to a radius \( r = 7 \text{ cm} \). Additional information was obtained on the low frequency oscillations which are generated spontaneously in the plasma and the total radiation of the arc was measured. Finally a question which was left in connection to the conservation of particles was resolved.

In Chapter 3 the results are reported which were obtained by feeding the hollow cathode discharge with other gases than argon. By doing so not only the ion mass is varied but, because of the different atomic properties of the various gases, the whole situation in the arc may be changed. It turned out that the nitrogen, the neon and the helium arc are rather similar to the argon arc, but the hydrogen arc appears to be quite different.

Chapter 4 deals with special ways of operation of the arc, in particular so far as the neutral particle flow is concerned. Additional gas was fed to the arc and a diaphragm was placed closely around the
arc. Besides for the study of neutral gas-plasma interaction, these experiments are also of interest in connection to the separation of isotopes. So are the experiments with hollow cylindrical plasma columns which are discussed in Chapter 5.

In Chapter 6 is shown that due to FLR effects the radial gradient in the electron temperature may be the cause of the mass rotation of the plasma.

Chapter 7 is concerned with the energy transport in the arc. The power balance of the ions in the positive column is in agreement with the usual fluid theory, but in the energy balance of the electrons non stationary terms have to be taken into consideration in order to explain a large drain of energy in radial direction.
2. SUPPLEMENTS TO THE ANNUAL REPORT 1974

2.1. Improved Thomson scattering measurements (n_e T_e)

These measurements are described in detail in Lit. 4.

In connection to the plasma under discussion the main results were:

- The electron temperature, T_e, decreases from the cathode towards the anode-like T_i (Fig.2). Near the cathode the measurements are impeded by the fact that due to the higher values of T_e the scattered radiation is distributed over a larger wave length range and its peak intensity does not raise clearly enough above the fluctuation level of the light emitted by the plasma. (Only a more powerful laser could bring here the required improvement.)

- Fig.3 shows that T_e drops sharply in the region next to the core - in contrast to T_i which is constant with radius.

- The plasma density at the centre, n_e(o), is about \(10^{14}\) part./cm\(^3\) and does not change much along the axis - in agreement with previous Langmuir probe measurements (see section 4.2 of Lit.2).

- In the range of B used in our experiments (1500 - 5100 Gauss), the plasma density is at maximum for cathodes of about 1 cm diameter. The d = 6 mm cathode produces clearly a less dense plasma. This may be due to FLR effects - under standard conditions \(r_{ci} \approx 0.5\) cm. Cathodes with a diameter larger than 2 cm tend to generate hollow plasma columns.

- The fluctuations in the plasma density are larger than expected at first, and in agreement with the high speed streak photographs (Fig.4).

2.2. Far off-axis spectral measurements of T_i and \(\Omega\).

So far spectral measurements of the ion temperature and the plasma rotation were made at radii \(0 \leq r < 4\) cm (see Fig. 7 of Lit.3). By moving the electrode supports laterally (Fig.3 of Lit.2) it is possible to place the arc 3 cm outside the centre of the machine and to extend the spectral measurements up to \(r = 7\) cm.\(^*)\) At \(r = 7\) cm the intensity of the spectral lines is three orders of magnitude smaller than at the centre, and the

\[*\) Under this condition the core of the positive column is excentric with respect to the wall, and the magnetic axis does not coincide any more with the centre of the arc. As expected from the facts that the wall of the vacuum chamber is relatively far away (\(R = 16\) cm) and that the magnetic field is rather homogeneous, these changes were found to be of no noticeable influence on the Doppler width and - shift measurements.
radiation which is reflected from the wall interferes with the line width and shift measurements. For this reason a black anodized aluminium sheath was mounted in the vessel, oppositely to the porthole where the optical measurements were made.

The measurements showed:
- The ion temperature, $T_i$, is constant with radius up to $r = 7$ cm (within the 10% accuracy of the measurements).

This is a somewhat surprising result, as $r = 7$ cm is far beyond the radius, $r_k$, where the kink in the radial density profile occurs and from whereon the plasma was supposed to be turbulent.
- The value of the rotational velocity, $\Omega$, is at larger radii (where the diamagnetic ion velocity predominates) found to be somewhat lower than derived before from pendulum and directed Langmuir probe measurements. A revised $\Omega(r)$ curve is shown in Fig.5, where the sign of $\Omega$ is also changed compared to Fig. 17 of Lit. 1 (the plus sign now refers to the direction of the electron diamagnetic current).

2.3. Total radiation from the positive column.

The radiation from the plasma was measured with a thermopile and with a HP 5082 - 4220 pin photo diode (sensitive to radiation in the range of 4000 to 10000 $\AA$). Under standard conditions the total radiation power was found to be about 40 Watt, of which about a quarter in the visible range.

Most of the radiation is in the ultraviolet and is probably due to recombination. In section 9.3.2. of Lit. 1 the recombination time in the core region is estimated to be $\tau_{\text{rec}} = 10^{-3}$ s $= \tau_{\text{ion}}$ (corona equilibrium). Thus about $1.6 \times 10^{-19} \times (n_e/\tau_{\text{rec}})^2 d^2 L X_1 = 35$ Watt is expected to escape from the positive column by radiative recombination, in agreement with the measurements. This is only about 1% of the total power which is handled by the positive column.

2.4. Low frequency oscillations.

Streak pictures of a narrow slit perpendicular to the plasma column
(see Fig.4) show large amplitude low frequency oscillations of the arc with the same frequency and depending in the same way on $B, I$ and $Q$ as the oscillations which were picked up by Langmuir probes (see chapter 8 of Lit.1). These oscillations are due to a $m = 1$ mode which propagates in the same direction and with about half the velocity as the mass rotation in the centre of the arc. As shown in section 7.3. of this report the magnitude of the displacements ($\Delta r = 5\text{mm}$) is in agreement with the measured values of the azimuthal a.c. electric field.

These oscillations may be of great importance for the energy transport in the arc. A closer inspection of Fig.4 shows that besides the main oscillations, fluctuations of higher frequency (about 100 kHz) are present in the plasma. These fluctuations were the principle obstacles for improvement of the accuracy of the Thomson scattering measurements.

As the frequency of the oscillations does not depend on $z$, whereas the plasma parameters $T_i, T_e$ and $\Omega$ vary considerably along the axis, the mode represents apparently an average property of the plasma column. This, together with the fact that we have clearly to do with a non linear phenomenon makes a theoretical treatment difficult. A first step in this direction was made by Janssen, who developed a non ideal MHD theory to give proper account of the fact that the contribution of the electric field to the mass rotation of the plasma is much larger than the diamagnetic contribution (Lit.5). The F.L.R. theory of Rosenbluth and Simon was extended by Nagarajan for the case that the axial variation of the plasmaparameters is comparable to the variation over an ion cyclotron radius. The corrections to the original theory turned out to be of no importance (Lit. 6).

In the previous report we chose among the available linear theories for the drift dissipative instability (Lit.1). The observed frequency agrees well with the theoretical expression:

$$\omega^* = \frac{T_e}{m_e} \left( \frac{\partial \ln n_e}{\partial x} \right) \left( 1 + \eta \right) K_c$$

(1)

$$\eta = \frac{\partial \ln \Omega}{\partial \ln n_e}$$

if the measured profiles of $n_e$ and $T_e$ are used and $K_c$ is taken equal to $1/x$. 

2.5. Effect of the radial gradient in $T_e$ on the particle balance.

In the absence of radial temperature gradients the radial particle flux is given by:

$$ n_e v_r = - \frac{e}{\omega_{ce}^2} \frac{3}{3r} \left[ n_e (kT_i + kT_e) \right] $$

(2)

The corresponding contribution to the particle conservation equation for a cylindrical plasma column with a Gaussian density distribution is (Eq. 41 of Lit. 1):

$$ \frac{1}{r} \frac{\partial}{\partial r} r n_e v_r = \left( \frac{4}{q^2} - \frac{8\pi^2}{q^4} \right) D n_i $$

It was surmised that close to core ($r < q\sqrt{2}$) other terms must make a negative contribution to the particle conservation equation. It is now realized that the strong radial gradient in the electron temperature close to the core (Fig. 3) may lead to a vanishing radial contribution of the particle balance. Kinetic theory analysis of the radial particle flux yields (Lit. 7):

$$ n_e v_r = - \frac{e}{\omega_{ce}^2} \frac{3}{3r} \left[ n_e (kT_i + kT_e) \right] - \frac{3}{2} n_e \frac{\partial T_e}{\partial r} $$

(3)

which in case $T_i$ does not depend on radius reduces to:

$$ n_e v_r = - \frac{e}{\omega_{ce}^2} \frac{3}{3r} \left( T_i + T_e \right) \frac{\partial n_e}{\partial r} - \frac{1}{2} n_e \frac{\partial T_e}{\partial r} $$

(3a)

According to Fig. 3 the second term on the right hand side of eq. 3a gives a contribution of the proper sign and magnitude in the particle conservation equation. The radial particle flux vanishes in case $(T_e + T_i) = n_e^2$ or $(T_e + T_i) = \exp \left(-2r^2/q^2\right) \neq 0$.

*) It may be noted that the parameter $\eta = \ln T_e/\ln n_e$, which plays an important role in the theory of the drift oscillations, reaches the critical value 2 in this case.
In the region next to the core such a radial dependence of $T_e$ is very
well possible. The $T_e$ measurements are, however, not accurate enough to
give a decisive answer.

At larger radii $\frac{\partial T_e}{\partial r} = 0$ and other contributions to the particle
balance must come into play (neutral particles and maybe turbulence). A
complete treatment is complicated by the fact that $\tau_e$ depends on $n_e$ and $T_e$
($\tau_e \sim n_e^{-1} T_e^{3/2}$).

3. VARIOUS GASES.

As shown in our previous report (Lit.1), the d.c. measurements made
on the positive column of the argon arc are generally in good agreement
with the usual two fluid theory.
Besides an experimental check of the theoretical formulas by varying
$n_e, T_i, T_e, B, \phi$ and $E$ (generally not independently), it seems also
desirable to vary the ion mass $m_i$. For that purpose the arc was run with
various other gases: $H_2, He, N_2$ and $Ne$. Though the plasma is highly ionised
(\(\alpha > 95\%\)) the values of its parameters are also determined by the atomic
processes suffered by the neutral particles, like ionization, recombination
and charge exchange which differ for the various gases. At every way of
operation of the gas discharge the plasma finds its own equilibrium situ­
ation which may differ considerably from the situation in the standard
argon arc.

3.1. D.C. properties.

Table 1 shows some plasma data which were measured in arcs fed with
various gases under standard conditions. The plasma density, $n_e$, and the
electron temperature, $T_e$, are absent in this table as it turned out to be
impossible to make with the present 30 J ruby laser Thomson scattering
measurements in other gases than argon and helium.
In the table are also shown the maximum ionization cross sections for the
various gases and the voltages where the maximum is reached (from Lit.8).
The voltage over the arc is clearly lower for gases with a higher cross
section for ionization.

All arcs are started with argon gas. The desired gas is fed addition­
ally to the arc, whereupon the argon feed is stopped.
### Table 1 - D.C. values of arcs fed with various gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>$X_i$</th>
<th>$\sigma_{i \text{ max}}$</th>
<th>$E_{\text{opt}}$</th>
<th>Color Arc</th>
<th>$V_{\text{arc}}$</th>
<th>$T_i(0)$</th>
<th>$T_i(50)$</th>
<th>$\Omega_{\text{opt}}(0)$</th>
<th>$\Omega_{\text{opt}}(50)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15.75</td>
<td>3.1</td>
<td>70</td>
<td>blue</td>
<td>70</td>
<td>9 ± 1</td>
<td>3.6±0.3</td>
<td>4.5±0.5</td>
<td>2.5±0.3</td>
</tr>
<tr>
<td>$N_2$</td>
<td>14.5</td>
<td>1.5</td>
<td>100</td>
<td>light blue</td>
<td>115</td>
<td>8 ± 1</td>
<td>3.3±0.4</td>
<td>4.8±0.5</td>
<td>3.0±0.5</td>
</tr>
<tr>
<td>Ne</td>
<td>21.6</td>
<td>0.8</td>
<td>160</td>
<td>pink</td>
<td>110</td>
<td>7.8±1</td>
<td>4.0±0.4</td>
<td>5.0±0.5</td>
<td>3.0±0.5</td>
</tr>
<tr>
<td>He</td>
<td>24.6</td>
<td>0.37</td>
<td>120</td>
<td>faint-pink</td>
<td>210</td>
<td>11±2</td>
<td>8±2</td>
<td>5±1</td>
<td>3.5±1</td>
</tr>
<tr>
<td>$H_2$</td>
<td>13.6</td>
<td>0.65</td>
<td>60</td>
<td>faint-l. blue</td>
<td>180</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$X_i$ = ionization potential in $V_i$; $\sigma_{i \text{ max}}$ = maximum ionization cross section in $10^{-16} \text{ cm}^2$; $E_{\text{opt}}$ = electron energy in eV corresponding to $\sigma_{i \text{ max}}$; $V_{\text{arc}}$ = voltage over the arc in V; $T_i$ = ion temperature in eV; $\Omega_{\text{opt}}$ = rotational mass velocity at $r = 0$ in $10^5 \text{ rad/s}$.

The nitrogen arc is very similar to the argon arc, only the radial gradient in the density is somewhat steeper. The neon arc resembles also the argon arc, but its operation is somewhat less stable. Helium and hydrogen vacuum arcs are difficult to run because of unfavourable I-V characteristics leading to unstable operation. Though the arcs are operated with a current stabilized rectifier, the use of these gases requires an additional resistance of about 1 $\Omega$ in series with the arc. Moreover the high voltage drops in the helium and the hydrogen arcs cause a very heavy wear of the electrodes which makes operation of these arcs less easy.

Apparentely the ion temperature $T_i$, and the rotational velocity $\Omega$ are approximately the same for the various arcs, with the hydrogen arc possibly excepted. As the ion temperature of the hydrogen arc cannot be measured directly, the profile of the $H_\beta$ atom line (with very weak intensity) was used hoping that, like found with the other gases $T_{\text{rot}}(0) = T_i(0)$. The spectral width of the $H_\beta$ line is about 0.3 $\AA$, indicating that $T_{\text{rot}}(0) \leq 0.6 \text{ eV}$ (*) (Stark broadening is expected to be as large as Doppler broadening).

*) Comparable data were found by Gibbons and Mackin (Lit.9) in an arc with gas feed at the anode.
3.2. **Low frequency oscillations.**

In the theoretical expression for the frequency of the drift oscillations, the radial e-folding length squared, \( q^2 \), is present:

\[
\omega^* = \frac{2 T_e}{(m_e c q^2)} \text{ (see Lit.1, Eq.45a)}
\]

As \( q^2 \) depends (weakly) on \( m_i \), the l.f. oscillations are expected to depend also on \( m_i \). The results of the measurements are shown in Fig. 6. It follows from Table 1 that the plasma parameters in the various arcs do not differ very much and thus it may be conjectured that the observed frequency shifts are mainly due to variation of \( m_i \).

The frequency of the oscillations in the nitrogen plasma is about 1.5 times the frequency found in argon and depends in the same way on \( B \), \( Q \) and \( I \). A factor of about 1.5 is also found between the \( q^2 \) values of argon and nitrogen. In the neon plasma two frequencies are found and comparison is not possible at the present state of the theory. In the helium plasma the frequency is about three times higher than in argon, whereas the ratio in the \( q^2 \) values is about 2.5 - thus again reasonable agreement with the theoretical expression of \( \omega^* \) is obtained. In the hydrogen plasma more frequencies are present and no comparison with the other gases can be made.

An uncertainty in this discussion stems from the fact that in reality \( \omega^* \) depends not only on the radial \( n_e \) profile, but also on the radial \( T_e \) profile (see section 2.4) which is only known for argon.

Finally a remark on the influence of impurities on the frequency of the l.f. oscillations may be made. During long series of measurements the frequency may shift noticeably. For a new cathode tube it may take an hour before constant values are reached (see Fig.7); for used cathodes the shift is less. A possible cause for this effect may be that gases which are absorbed by the cathode material (tantalum) are released when the cathode comes into operation. An impression of the effect of impurities may be obtained from Fig.8 where the frequency of the l.f. oscillations is shown for mixtures of argon with nitrogen and hydrogen.
Another possible cause for the frequency shift is gradual wear of the cathode tubes which may lead to shifts in the values of the plasma parameters. In this relation it is of interest to note that if the arc is operated with a shield around the cathode (see Fig.1 of Lit.2) the frequency of the oscillations is found to be about 2 kHz lower than without a shield.

4. FLOW AND DISTRIBUTION OF NEUTRAL PARTICLES

The fact that the plasma of the positive column is highly ionized does not mean that the neutral particles do not play an important role in the discharge. The gas discharge (of which the positive column under investigation is a part) results as an interplay between the applied voltage and the gas. The created plasma does not only depend strongly on the amount of gas which is fed to the discharge, but also on the way the gas feed (and pumping) take place.

The distribution of the neutral particles is very difficult to measure as ionization gauges can only be placed far away from the plasma, and the neutral pressure, \( p_1 \), which is measured at a certain place in the vacuum chamber does not give much information on the pressure elsewhere. Besides on the gas flow the distribution of the neutrals depends on the interaction of the plasma with the neutral gas, like ionization (mainly in the active zone), recombination (mainly at the wall and at the anode) and charge exchange (pumping action of the discharge). Fig. 9 shows \( p_1(z) \) measured at the various portholes at a distance of 50 cm from the centre, beyond the wall of vacuum chamber \((R=16 \text{ cm})\). Together with the tentative \( p_1(r) \) curve shown in Fig.23 of Lit.1 this gives some idea about the distribution of the neutrals.

It is equally difficult to appreciate the effect which a change in the flow pattern of the neutrals has on the plasma. E.g. if a beam of neutral particles is directed towards the core of the positive column (in order to know more about the role of the neutral particles) the processes in the active zone depend on what happens to the external plasma. Changes in the positive column (like length and neutral particle density) are "felt" in the active zone.
It is possible to sustain the discharge by feeding the gas from the side or through the anode. We then still have a hollow cathode discharge in the sense that the hot glowing cathode tube is of vital importance for the discharge, but the plasma differs considerably from the plasma which is generated by feeding the gas through the cathode. Sometimes it seems convenient to consider the active zone at the cathode as a place where the instreaming gas is transformed into a highly ionized plasma, but this picture is not quite correct. The hollow cathode discharge is just a low pressure arc with a very efficient operating cathode; the applied magnetic field leads to partial confinement of the plasma particles and to (unknown) ionization and heating processes in the active zone which occur in and near the hollow cathode.

4.1. Additional injection of gas.

A flow channel for gas injection is easily obtained by replacing the Langmuir probe in the probe mount shown in Fig.8 of Lit.2 by a 6 mm i.d. tantalum tube. This opens the possibility of injecting a beam of neutral particles into the arc at various radii and axial positions (or alternatively to suck off neutral gas, e.g. in order to analyze it in a mass spectrometer).

Perpendicular injection at \( z=60 \text{ cm} \) of \( 2 \text{ cm}^3 \text{ NTP/s} \) argon gas at a distance \( r=2 \text{ cm} \) from the centre of the arc causes a drop in the ion temperature at \( z=60 \text{ cm} \) from \( T_i=3.6\text{eV} \) to \( T_i=1.7\text{eV} \); in this case \( \Omega_o \) drops from \( 2.4 \times 10^5 \text{ rad/s} \) to \( 1.2 \times 10^5 \text{ rad/s} \). The same values of \( \Omega_o \) and \( T_i \) are measured when the gas stream is directed obliquely upstream (remember the plasma streams from the cathode towards the anode with a velocity of \( 6 \times 10^4 \text{ cm/s} \)). When directed downstream the effect of the neutral particles on \( T_i \) and \( \Omega_o \) is negligible. These measurements indicate that the ion temperature depends on ion-neutral collisions and support the calculations made in section 6.2 of Lit.1 where the axial gradient in \( T_i \) was explained by charge exchange collisions. An exact evaluation is complicated by the fact that with extra injection of neutral particles their density raises everywhere in the vacuum chamber.

Some information on the processes which occur in the active zone may be obtained by injection of neutral gas in the direct vicinity of the
cathode. The ion temperature at the middle of the positive column $T_i$ (z=60 cm), drops from $T_i = 3.6$eV to $T_i = 2.8$eV when 2 cm$^3$ NTP/s extra gas is injected at a radial distance $r=2$ cm just in front of the cathode. $T_i$ (z=60 cm) drops to 2.3eV in case the extra gas is injected at the wall of the vacuum chamber. The rise in neutral gas pressure (measured at porthole 3) is practically the same in both cases. The voltage over the arc decreases from 80 V to 75 V in the first case, but increases to 90 V in the second case.

4.2. Operation of the arc with gas feed at the wall.

The transition from the experiments which are mentioned in the preceding section to operation of the arc with gas feed at the wall is simple: one just has to stop the gas feed through the cathode and the discharge continues with a hot glowing cathode. If the arc is operated under "standard" conditions with a d=9 mm cathode (I =50A; Q =2 cm$^3$ NTP/s; B=3400 Gauss) the ion temperature drops from $T_i$ (z=60 cm) = 3.6eV to $T_i$ (z=60 cm) = 0.75eV, if 6 cm$^3$ NTP/s extra gas is injected at the wall. The temperature $T_i$ (z=60 cm) jumps to 2.3eV if the gas feed through the cathode is shut off, and remains practically constant if after that the gas feed at the wall is decreased - see Fig. 10. This is in contrast to what happens when Q is decreased under operation with gas feed through the cathode.

The rotational velocity $\Omega_o$, is found to be $2.3 \times 10^5$ rad/s and the direction of the rotation is the same as before (direction of the electron diamagnetic current). Apparently the properties of the plasma in the positive column do not change essentially by changing the place of the gas feed.

4.3. Operation of the arc with gas feed through the anode.

In order to open the possibility to feed gas through the anode, the anode was supported with a similar system as used for the cathode (Lit.2 Fig.3). The values of $\Omega_o$ and $T_i$ at z=60 cm are practically the same as when the gas is fed through the cathode. But more towards the cathode (smaller values of z) $\Omega_o$ and $T_i$ are lower than by feeding gas through cathode (Fig.11). The arc column is more homogeneous and accordingly the contours of the core boundary are sharper. It seems worthwhile to make a closer investigation of this way of operation, which was used
before by Mackin and Gibbons (Lit.9). Fig.11a shows the (I,V) characteristic.

4.4. The diaphragm.

A diaphragm fitting closely around the core of the arc was placed between two sections of the machine (at z = 30 cm). As shown in Fig.12 the cylindrical opening, made of watercooled tungsten, has a diameter of 2 cm, whereas a "standard" cathode of 1.6 cm outer diameter was used. Proper operation of the discharge is only possible if the arc is centered well in the diaphragm.

The diaphragm does not only affect the transport of particles, momentum and heat in the plasma, but also acts as a pumping baffle. With a gas feed \( Q \approx 4.5 \text{ cm}^3 \text{ NTP/s} \) the neutral gas pressure, \( p_0 \), at the cathode side of the vacuum chamber rises from \( 10^{-3} \text{ Torr} \) to about \( 2 \times 10^{-3} \text{ Torr} \), whereas at the anode side \( p_0 \) drops to about \( 4 \times 10^{-4} \text{ Torr} \). Thus the diaphragm affects the plasma also indirectly via the neutrals.

So far measurements were only made with Langmuir probes and with the Fabry-Perot interferometer. They yielded the following information:

- The radial density profile is affected by the diaphragm. At the cathode side (\( z \approx 0 \text{ cm} \)) it is about the same, but at the anode side (\( z \approx 66 \text{ cm} \)) the \( n_e(r) \) profile is steeper than without diaphragm. As the perpendicular particle flux is not much affected by the diaphragm, this indicates that longitudinal particle losses are also of importance in the particle balance.

- The ion temperature is not much affected by the diaphragm; like without diaphragm, \( T_i \) is constant with radius. If the valve of the vacuum pump at the anode side is closed, the pressure at the anode side of the vacuum chamber raises from \( 4 \times 10^{-4} \text{ Torr} \) to \( 10^{-2} \text{ Torr} \) and as expected the ion temperature near anode, \( T_i (z = 100 \text{ cm}) \), decreases from 1.6eV to 0.6eV.

- The rotational velocity of the plasma, measured at the middle of the arc, \( \Omega_0 \) (\( z = 60 \text{ cm} \)) decreases from \( 2.5 \times 10^5 \text{ rad/s} \) to \( 1.5 \times 10^5 \text{ rad/s} \). Increase of the pressure \( p_0 \) reduces \( \Omega_0 \) still more.

*) Even with floating baffle the discharge sometimes (particularly at low values of B) changes its character and extends to the rim of the water-cooled flange which holds the diaphragm. Its diameter becomes 5 cm and the arc voltage increases from 70V to 150V. No studies were made of this mode of operation.
The radial electric field is strongly affected at radii $r > 2$ cm (closest possible distance to the core of a Langmuir probe). These measurements together with the $\tilde{\Omega}_o$ measurements in the core make it possible to draw a tentative $E(r)$ curve (Fig. 13). The decrease in $\tilde{\Omega}_o$ and in $E$ indicate that the radial gradient in $T_e$ is decreased by the diaphragm. As most of the power in the arc is handled by the electrons, the diaphragm is expected to have a large effect on the power balance.

The most dramatic effect is observed in the low frequency oscillations. Depending on the gas discharge parameters their amplitude is reduced drastically on both sides of the diaphragm. The same observation was made by Woo and Rose (Lit.10) who recommended to use this effect for obtaining a "quiescent" plasma. Apparently the diaphragm acts as a damping device for the low frequency oscillations.

These preliminary results seem to indicate that more systematic measurements of all the plasma parameters at various axial and radial positions in the presence of the diaphragm may yield further information on the particle- and energy balance of the plasma.

5. THE HOLLOW PLASMA COLUMN.

In addition to the normal cylindrical cathode tubes, cathodes consisting of two concentric cylinders were used in order to generate hollow plasma cylinders (see Fig. 14). Two sizes were used: a cathode (C1) made of tantalum tubes $\phi 20 \times 1,5$ and $\phi 13 \times 1$, and a cathode (C2) with a $\phi 30 \times 2$ outer tube and a $\phi 20 \times 1,5$ inner tube. The areas between the cylinders are respectively $1.4 \text{ cm}^2$ and $3.0 \text{ cm}^2$, compared to the $1.3 \text{ cm}^2$ area of the standard cathode $\phi 13 \times 1 \text{ mm}$.

Like observed before with the normal cylindrical cathodes, the ion temperature, $T_i$, is constant with radius, but decreases in axial direction towards the anode. The temperature of the neutrals also equals the ion temperature. The values of $T_i$ and $T_n$ are close to the values found with the cylindrical cathodes if operated with the same electric current density and gas flux.
Fig. 15 shows the intensity of the A II $4806 \AA$ line and the much weaker A I $4201 \AA$ line as function of the radius for the large cathode, C2, at $z = 0$ cm (for $I = 100$ A and $I = 200$ A) and at $z = 60$ cm ($I = 100$ A)*). Similar profiles were found with the C1 cathode. The intensity profiles are clearly hollow, in contrast to what is found with a normal cathode. As the intensity of the spectral line varies $- n_e \exp - (1/kT_e)$ the intensity profile would represent the $n_e(r)$ profile if $T_e$ were constant with radius. A hollow radial intensity profile would, however, also be found in case the electron temperature drops somewhat at the centre. A definite choice between these two alternatives could not be made, as we were not able to make Thomson scattering measurements on large diameter cathodes (see section 2.1.).

The results of the Doppler shift measurements are shown in Fig. 15a. Inside the core region $v_\psi$ is not proportional to $r$, (as is the case for the normal cylindrical cathodes), but $\Omega$ approaches zero at the centre of the arc column. The $v_\psi(r)$ profile is about as expected when $T_e$ is constant with radius inside the cathode diameter and changes rapidly outside, like in Fig. 5 (see chapter 7).

6. THE ORIGIN OF THE MASS ROTATION

The angular mass velocity, $\Omega$, is expected to be the sum of the diamagnetic- and guiding centre drift angular velocity (magnetic field gradient $\partial B_z/\partial r$ and centrifugal forces neglected).

$$\Omega = \Omega_{\text{di}} + \Omega_E$$

$$\Omega_{\text{di}} = \frac{v_{\text{di}}}{r}, \quad \Omega_E = \frac{v_E}{r} = -\frac{eE}{rB}$$

This relationship was confirmed by direct measurements for the plasma under discussion (see Fig. 32 of Lit.1). The question remains what is the origin of the radial electric field?

* The optical analyser scans radially through the arc with an (imaginary) slit of about 1 mm width (<<d) and a beam divergence of about 1/10.

This leads to a reduction of 20% in the ratio between the maximum and minimum intensity $\sqrt[d_{\text{out}}]{d_{\text{in}}} / (d_{\text{out}} - d_{\text{in}})$. For both cathodes (C1 and C2) $I_{\text{max}}/I_{\text{min}}$ is expected to be about 1.8, whereas a lower value 1.5 is found from Fig. 15. Also the reason for the asymmetry of the intensity profiles is not known.
The radial current to the wall is negligible and the radial diffusion of the plasma particles is ambipolar. The radial particle transport is within a factor two determined by "classical diffusion", which indicates that the radial particle flux is due to the friction in azimuthal direction between the ions and the electrons: \( v_{er} = v_{ir} = (v_{di} - v_{de})/\omega_{ce}r_{ei} \). (As \( \omega_{ce}r_{ei} \) the ambipolarity is automatically fulfilled and no radial electric field has to set up.)

If for some reason the ions and the electrons tend to diffuse with different rates through the magnetic field, a radial electric space charge field will set up until \( v_{er} = v_{ir} \). As mentioned already in a previous report (Lit.1) Simon pointed out that ion - ion collisions may lead to an extra radial velocity of the ions and according to Kaufman a radial electric field is set up to such a value as to effectively destroy the flux caused by ion - ion collisions:

\[
E_{r} = \frac{kT_{i}}{e} \frac{n_{i}^{2}}{n_{e}} \frac{\partial n_{e}}{\partial r} \quad \text{ (eq. 40 of Lit.1)}
\]

This radial electric field is pointing inwardly, and according to Eq. (4) it corresponds to a vanishing mass rotation. However, the plasma is rotating and near the core the observed field is five times larger than predicted by Kaufman. Moreover it decreases with radius outside the core region, whereas according to Kaufman it should increase linearly with radius.

As already pointed out in Lit.11 a radial gradient in the electron temperature in combination with finite Larmor radii of the ions may yield a contribution to the mass rotation in case the electron temperature, \( T_{e}(r) \), falls off more rapidly with radius than the plasma density, \( n_{e}(r) \), whereas the ion temperature shows the smallest variation:

\[
1_{T_{i}} > 1_{n_{e}} > 1_{T_{e}} = r_{ci} \left( \frac{\partial T_{e}}{\partial r} \right) = \frac{1}{1_{T_{e}}}; \quad \frac{\partial n_{e}}{\partial r} = \frac{1}{1_{n_{e}}}; \quad \frac{\partial T_{i}}{\partial r} = \frac{1}{1_{T_{i}}}
\]

Under this condition an ion experiences along its Larmor circle (radius \( r_{ci} \)) a varying friction with the electrons - more collisions take place where \( T_{e} \) is lower. In the first approximation the average friction force experienced by an ion is augmented by an amount:
The extra friction force on the ions tends to make \( v_{ir} \) larger than \( v_{er} \) by an amount \( \Delta v_{ir} = c \Delta f_{FLR}^{FLR}/eB \). Like the Simon diffusion this extra radial ion current has its origin in viscous effects on the ions. As it is not accompanied by an equally large radial electron current it is (analogous to the Kaufman case) prevented by an electric field such that \( \nu_i E_{r}^{FLR} = -\Delta v_{ir} \) (\( \nu_i = \frac{e}{m_i \omega_c i_i, e} \) is the perpendicular mobility of the ions). From Eq. 5 it follows:

\[
E_{r}^{FLR} = -\frac{4}{\pi} \frac{kT_i}{e} \left( \frac{3}{2} \frac{1}{T_e} - \frac{1}{n_e} \right)
\]  

(6)

The total radial electric field is approximately:

\[
E_{r}^{TOT} = E_{r}^{K} + E_{r}^{FLR} = -2 \frac{kT_i}{e \lambda T_e}
\]  

(7)

The effect of the transverse viscosity due to ion-ion collisions is largely compensated by an oppositely directed part of the extra friction between ions and electrons.

Combination of Eq. (4) and Eq. (7) yields for the mass velocity:

\[
\Omega = \frac{kT_i}{m_i \omega_c i_i} \left[ \frac{2}{\lambda T_e} - \frac{1}{n_e} \right]
\]  

(8)

The effect of the centrifugal force is neglected in this equation, because of its relative small importance even in the regions where \( \Omega \) is large.

Within the accuracy of the measurements the relation between \( \Omega(r) \) (Fig. 5) and the radial density - and temperature profiles (Fig.3 and Fig.10 of Lit.2) is properly described by Eq. (8). The angular velocity is large.
in the direct neighbourhood of the core where $\frac{\partial T_e}{\partial r}$ is large and smaller and oppositely directed (corresponding to $\Omega_{\text{e}}$) at larger radii where $\frac{\partial T_e}{\partial r} \to 0$.

7. THE ENERGY TRANSPORT

7.1. Overall power flow.

The total power which is fed to the arc follows directly from the $(I,V)$ characteristic and is for operation under standard conditions ($I = 100\,\text{A}$; $V = 70\,\text{V}$) about 7 kW. Practically all this power is finally removed from the system by the water cooling of the electrodes and the wall. The question where and how this power flows is solved differently in the three regions of the discharge - the cathode region ($\Delta V = 45\,\text{V}$), the positive column ($\Delta V = 15\,\text{V}$) and the anode region ($\Delta V = 10\,\text{V}$). A sketch of the overall power balance of the discharge including only the main contributions is shown in Fig. 16.

In the cathode region electrons which emerge from the hot glowing cathode are accelerated in a voltage difference of about 45V, which is an optimum value for ionization of neutral argon atoms (see Lit. 8). Depending on the acquired velocity and the place where they are created, the ions are either accelerated in the direction of the cathode (which is heated by them) or are dragged with the electrons in the direction of the anode with a velocity of about $6 \times 10^4 \,\text{cm/s}$. (see Lit. 1 page 34). With Stephan-Boltzmann's law and the measured temperature profile along the cathode tube it is found that the black body radiation of the cathode amounts to about 0.8 kW. The heat conduction along the cathode tube amounts to about one tenth of this amount, so that all together roughly 1 kW is lost at the cathode tube. For ionization ($\chi_e = 15.75\,\text{eV}$) and heating ($T_i = 8\,\text{eV}$; $T_e = 12-16\,\text{eV}$) of a flow $Q = 4.5\,\text{cm}^3\,\text{NTP/s}$ argon gas 0.8 kW power is needed. Thus of the 4.5 kW power which is used in the cathode region, about 3.5 kW flows into the adjacent region of the positive column; 0.8 kW of this amount is invested in the plasma particles and the rest flows as heat into the positive column.

At the other side of the discharge (where $T_e = 2\,\text{eV}$ and $T_i = 1\,\text{eV}$) electrons which are accelerated in the anode region deliver about 1 kW
power at the anode ($\Delta V = 10$ V). The heat flow from the positive column to the anode amounts to about 0.5 kW. Recombination of particles which flow toward the anode ($v_z \approx 6 \times 10^4$ cm/s) contribute to another 0.5 kW. Altogether about 2 kW power has to be removed from the anode by water-cooling.

About 4 kW power reaches the wall via the plasma. Whereas the positive column is the most interesting part of the discharge for studies in plasma physics, for the gas discharge it merely serves to maintain a conducting path for the current and the heat between the cathode and the anode. 1.5 kW Joule heat is dissipated in the plasma of the positive column. 0.5 kW is stored in particles which leak through the magnetic field and reach the wall where they recombine.

Most of the heat is conducted by the electrons and this heat conduction is proportional to $T_e^{5/2}$ and $\frac{\partial T_e}{\partial z}$. Of the 2.7 kW heat which enters the positive column at the cathode side, only 0.5 kW reaches the anode. Thus 2.2 kW is "left behind" due to the axial gradient in the electron temperature. There is a surplus of about 3.5 kW in the power balance of the electrons, which is probably transported away in radial direction by a special type of conduction (see section 7.3). Radiation (40W) may be neglected (see section 1.3).

The decrease of $T_i$ and $T_e$ towards the anode makes it useful to distinguish in the positive column in axial direction three regions of 40 cm length and to make up the power balance in each of them. In the core of the argon arc the parameter $\omega_{ci,i}$ ($= 10^{-1} \frac{T_i^{3/2}}{T_i}$ under standard conditions) is in these regions respectively larger, about equal and smaller than one. This parameter is of importance for the perpendicular heat transport of the ions. The energy drain by the electrons is proportional to $T_e^2$, so that the larger part of the radial power transport occurs in the region next to the cathode.

7.2. Power balance of the plasma in the positive column.

For each species of particles the energy transport equation for a plasma in the stationary state is (see Lit.7):

-20-
The tensor in the brackets of Eq. (9) represents the sum of the total energy transport with velocity \( \mathbf{v} \) (convection), the heat flux \( \mathbf{q} \) (conduction) and the work done by the total pressure forces \( \Pi \) is the stress tensor). The other terms represent respectively the Joule dissipation, the momentum transfer between ion and electrons and the heat \( Q \), generated in a gas of particles of a given species as a consequence of collisions with particles of the other species. The values of the various terms of Eq. (9) integrated over the three different sections of the positive column are shown in Table II for the ions and for the electrons (see also Lit.12).

The numbers are only approximate. Neither the theory nor the experiments are more accurate than a factor two. It is evident that:

- the electrons handle a much larger part of the energy transport than the ions (roughly 20 times)
- for the ions the losses and the gains are in balance within the accuracy of the various contributions; the contribution of the perpendicular heat condition is small due to the constancy of \( T_i \) with radius.
- The gains far exceed the losses for the electrons.

It is concluded that the "classical" power balance is fulfilled by the ions, but that the electrons do not obey the stationary power balance equation.

7.3. **Energy drain by the electrons.**

As suggested in Lit.13, the surplus in the power balance of the electrons may be drained off in radial direction by the strong low frequency oscillations which were discussed before (see Lit.1 and section 2.4. of this report). Formulated differently it is necessary to take the time dependent part of the power balance of the electrons also into consideration. The azimuthal a.c. electric field near the core \( E_\phi \simeq 2 \text{ V/cm} \) causes a perpendicular a.c. drift of the plasma particles with velocity \( \mathbf{v}_d \simeq 6 \times 10^4 \text{ cm/s}. \)
As the angular frequency of the oscillations $\omega = 10^5$ rad/s the particles move around their equilibrium position over a distance $\Delta r = \frac{v_d}{\omega} = 0.6$ cm. This agrees well with the direct observation made with a streak camera (fig.3).

Due to the phase difference which is shown in Fig.5 the oscillations cause a mixing of colder and warmer electrons. There is ample time for the equipartition of energy between the electrons ($\tau_{eq} (eq) = 10^{-8}$ s) - not between electrons and ions ($\tau_{eq,i} (eq) = (m_i/m_e)\tau_{eq} (eq) = 7 \times 10^{-4}$ s). Over a distance of 0.6 cm the phase of the oscillations varies about 90° and at the cathode side of the plasma column the electron temperature, $T_e$, varies about 6 eV. The perpendicular heat flow due to the drift oscillations is about

$$q_L^{(\text{drift})} = n v_d 2 \Delta r \frac{\delta T_e}{\delta r} \approx 6 \text{ W/cm}^2.$$ 

This heat flow is required to drain the surplus of 40 W per cm arc length away from the central part of the arc. As $\delta T_e/\delta r$ like $T_e$ decreases with $z$, $q_L^{(\text{drift})}$ decreases with $z$ in the same proportion as the power surplus. In conclusion it may be noted that apparently the drift oscillations are not so much of importance for particle transport (was suggested by Bohm in Lit.14) as for energy transport.

*) Though the plasma is periodically displaced over relatively large distances, the oscillations do not seem to affect either the stability of the transport of the plasma. As mentioned before the perpendicular loss rate is found to be within a factor two (experimental error limit) in agreement with the "classical" diffusion rate. This is confirmed by the fact that the oscillations in the plasma potential, $\varnothing$, and in the plasma density, $n_e$, are found to be in phase. The time average of the radial particle flux due to the alternating electric drift is expected to be:

$$n_e (r,z) \varnothing (r,z) \cos \left( \frac{\phi_n - \phi_\varnothing + \pi}{2} \right) = 0 \text{ for } \phi_\varnothing = \phi_n.$$
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REFERENCES:


Fig. 1. Experimental set-up

1 Vacuum vessel
2 movable cathode support
3 movable anode support
4 magnetic field coil
5 laser diagnostic equipment
6 Fabry-Perot interferometer
7 high speed camera
8 mass spectrometer
9 correlator and spectrum analyser
10 Langmuir probe
Fig. 2. Axial variation of electron- and ion temperature; $r = 0$; standard conditions. $T_e$ measurements at lower values of $z$ are impeded by the fact that the amount of scattered light in each wavelength "channel" becomes smaller by further broadening of the Doppler profile ($\Delta \lambda \propto T_e^2$) and finally drowns in the background fluctuations.
Fig. 3 Radial profiles of electron- and ion temperature (standard condition, z=60 cm).
Fig. 4 a. Streak photographs of the core of the arc (streak length 200 μs); slit width 0.5 mm; 
z = 60 cm; standard conditions for \( d_c = 9 \) mm.

Fig. 4 b. Same for various values of arc current \( I \).
Fig. 5. Angular mass velocity, $\Omega$, at the middle of the positive column, of a hollow cathode discharge as function of radius, measured from Doppler shift of the Al II 4861Å spectral line. Standard conditions; $z=60$ cm.

$\Omega = \Omega_{\text{Di}} + \Omega_{\text{E}}$

$\Omega_{\text{Di}}$ (diamagnetism of ions)
$
\Omega_{\text{E}}$ (electric drift) from Langmuir probe measurements.
Fig. 6. Frequency of the l.f. oscillations as function of magnetic field strength for various gases.

A d=9 mm cathode was used, operated with I=60 A; Q=2 cm³ NTP/s; L=120 cm.

For stable operation the helium arc was run with I=35 A and Q=5 cm³ NTP/s.
Fig. 7. Variation of frequency with time for a fresh cathode tube. Argon arc; standard conditions.
Fig. 8. Frequency of the l.f. oscillations in arcs operated with mixtures of various gases with argon.
Fig. 9a. Argon gas pressure measured (with ionization gauges) at various places in the vacuum chamber. Gas feed through the cathode; standard conditions.

Fig. 9b. Argon gas pressure inside hollow anode as function of arc current $I$. Gas feed through cathode; standard conditions.
Fig. 10. Operation of the arc with gas feed at the wall.
The voltage over the arc increases with decrease of gas feed Q whereas $T_i(z=60 \text{ cm})$ remains practically constant.
Fig. 11. Operation of the arc with gas feed through the anode (---) as compared with gas feed through the cathode (-----). Fig.11a. (I, V) characteristics. Fig.11b. $\Omega_0$ as function of axial position $z$. Fig.11c. $T_i$ as function of axial position $z$. 
Fig. 12. Drawing of the diaphragm.
Fig. 13. Floating potential and corresponding radial electric field as function of radius at z=60 cm.

--- without diaphragm (see Fig. 13 of Lit. 1).

--- with diaphragm at z=30 cm.
Fig. 14. The C2 cathode.
Fig. 15a. Radial profile of the intensity of the Al II 4806Å line in an argon arc operated with the C2 cathode.

- I = 200 A; z = 0 cm; T_i = 6.8 eV.
- I = 100 A; z = 0 cm; T_i = 3.6 eV.
- I = 100 A; z = 60 cm; T_i = 2 eV.

--- Intensity Al II 4201 Å line (x100); T_n = 3.6 eV.

Fig. 15b. Radial profile of the azimuthal mass velocity, υ_φ, of an argon arc operated with the C2 cathode.
Fig. 16. Overall power flow in the hollow cathode discharge fed with argon (standard conditions). In order to facilitate the calculation of the power balance in the positive column, it is divided in three regions where the parameter $\omega_{ci} T_i$ in the core is respectively larger, about equal and smaller than 1.