Experiments with a large sized hollow cathode discharge fed with argon

Citation for published version (APA):

Document status and date:
Published: 01/01/1973

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 23. Sep. 2020
EXPERIMENTS WITH A LARGE SIZED HOLLOW CATHODE DISCHARGE FED WITH ARGON

ANNUAL REPORT 1973

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

ANNUAL REPORT 1973

EURATOM - THE Group "Rotating Plasma"
C. BASTIAN
F. BOESCHOTEN
H. HEKMAN
R. KOMEN
H.P. RISKE
A. VAN IERSEL

This work was performed under the terms of the agreement between the Technische Hogeschool Eindhoven and the association Euratom, to conduct joint research in the field of plasma physics.

TH-Report 74-E-45
April 1974
ISBN 90 6144 045 9
CONTENTS

1. SUMMARY
2. APPARATUS
3. OPTICAL SPECTROSCOPY
   3.1. Improvement of the interferometric system
   3.2. Automatic data recording and evaluation
   3.3. Azimuthal velocity of the ions
   3.4. Ion temperature
4. LANGMUIR PROBE MEASUREMENTS
   4.1. L.P. characteristics
   4.2. Radial density profiles
   4.3. Floating potential
   4.4. Directional L.P.
5. PENDULUM MEASUREMENTS
6. COMPOSITION OF THE MEASUREMENTS
7. APPENDIX. Digital treatment of the interferometric data
   7.1. Automatic data acquisition
   7.2. Data handling

REFERENCES
EXPERIMENTS WITH A LARGE Sized HOLLOW CATHODE DISCHARGE FED WITH ARGON

1. SUMMARY

Several plasma parameters which are pertinent to the rotation of the plasma column of the hollow cathode discharge "John Luce" were measured. A description of this facility is given in TH - Report 73 - E - 35 (1973). Since the publication of this report several improvements to the device were made, noticeably concerning the construction of the electrodes and their supports.

The ion temperature, $T_i$, was measured with a Fabry-Perot interferometer; depending on arc current and gas flow $T_i$ may be varied in an Argon arc in the range of 1-10 eV. The magnetic field strength, $B$, is adjustable from 600-6000 Gauss. The plasma column is fully ionized, and for higher values of $T_i$ and $B$ it is also fully magnetized ($\omega_{ci} T_i > 1$).

Simultaneous Doppler-shift measurements of the $\text{A}^{II}$ line 4806 Å reveal that the plasma column rotates non-uniformly around its axis. (Order of magnitude of angular frequency is $10^5$ rad/sec) At larger distances from the axis the rotation was measured with a pendulum and with a directional Langmuir Probe. The object of the experiments is to disclose the connection between this rotation and the stability of the plasma column.

Langmuir Probes are used to measure radial density profiles under various conditions in the arc. A flat probe with its normal to the surface pointing in radial direction makes reliable ion density measurements possible, even in the presence of a magnetic field. Floating potential measurements were used in order to estimate the radial electric field strength and the drift velocity which is related to it. The electron temperature, $T_e$, is measured with less accuracy.
2. APPARATUS

The vacuum system and the system generating the magnetic field functioned properly and did not require any change, but for the electrodes and their support system some improvements were made.

Tantalum cathode tubes of 15 mm outer diameter and 13 mm inner diameter (Ø 15x13) mounted in the way as shown in Fig. 5 of TH - Report 73 - E - 35 lasted on the average for ten burning hours of an Argon arc operated with 100 Amp arc current and 4.5 ccNTP/sec gas feed. Under these conditions the evaporation rate was found to be about $2 \times 10^{-4}$ g/s or $2 \mu g$/Coulomb, ten times higher than MINNO (1969) found for a 3 mm cathode tube, operated at an arc current of 15 Amp and a gas feed of 0.2 ccNTP/sec. Smaller cathode tubes (Ø 8x6) lasted for a longer, bigger tubes (Ø 20x18.8) for a shorter time. For every new cathode a new copper piece had to be machined around which the Tantalum cathode tube had to be tightened by means of a shrunken stainless steel ring. This work has been overcome with a new construction (see Fig. 1), which allows replacement of the cathode simply by screwing a new Tantalum tube in a water cooled clamp. These cathodes also last longer, because the contact of the Tantalum with the Copper is better. A big improvement was also obtained by placing a Tantalum shield around the cathode tube. The deposition of Tantalum in the vacuum system is reduced considerably (by a factor of five) and the cathode tubes last still longer.

The construction of the anode was also simplified and improved. The contact between the Tungsten anode plate and the water cooled Copper is no longer obtained by brazing, but by pressing the parts together with a stainless steel screw-cap (see Fig. 2).

A drawing of the movable electrode support system may be found in Fig. 3 and a picture of the completed set is shown in Fig. 4. It allows continuous variation of the arc length without
any appreciable effect on the vacuum.

The neutral gas pressure in the vacuum chamber is about \(10^{-3}\) Torr. A water-cooled stainless steel disk was constructed, which may be mounted in the vacuum chamber. This provides for the possibility to lower the neutral gas pressure by differential pumping. Measurements with a hollow anode gave an indication about the neutral gas pressure in a tube which communicates with the arc. Pressures of about 1 Torr were measured, in agreement with \(\kappa n_o T_o\) (neutral gas) = \(\kappa n T\) (plasma) and with values mentioned by MINOO (1969).
3. OPTICAL SPECTROSCOPY

3.1. Improvement of the interferometric system

The high resolution interferometric set-up as described in the T.H. Report 73 - E - 35 was improved and applied to further measurements of the rotational and thermal velocities of the ions in the vacuum arc for different values of the arc current, I, the magnetic field strength, B, and the gas inlet, Q.

The ironcast pressure tank of the interferometer was replaced by a new housing which makes it possible to use the original invar interferometer mount (Halle). The former, though more compact, has been found eventually too sensitive to changes of the environmental temperature, which made tedious drift corrections necessary. With the invar mount and the same thermostatic stabilisation as before (± 0.05 °C), the drift expressed as an uncertainty on the wave length turned out to be below 1 milliÅngstrom. Accordingly, no drift correction had to be applied to the results.

3.2. Automatic data recording and evaluation

Previously, the plasma rotation has been evaluated graphically by recording a series of line profiles at different positions of the arc and comparing their mutual displacement. This exclusively analog method has two major shortcomings. First, the profiles taken at more than 1 cm from the axis were hardly readable due to their low signal to noise ratio. Secondly, any profile recorded at a given distance of the axis includes, besides the "true" component of emission at this radius, contributions due to outer regions of the arc which are sighted at the same time. A deconvolution, or inversion procedure has hence to be applied to the whole set of profiles, a piece of work far beyond the range of elementary graphical methods.

For these reasons, the spectroscopic data were sampled, digitalized and logged on paper tape using a 620 f (Varian) process computer, then transferred on magnetic tape for further treatment with the B 6700 (Burroughs) large computer of the THE. (See Appendix).
This way, the data could be evaluated reasonably up to 3 cm from the axis. Typical results of the deconvolution procedure are illustrated in Fig. 5a (light intensity versus radius) and Fig. 5b (line shift versus radius). It turns out that the direct interpretation of the displacement of the apparent profiles may underestimate the rotation 15 - 20 % in the region of maximum gradient of density, where an exact knowledge of the velocity field is determinant for diffusion or stability studies.

3.3. The Azimuthal Velocity of the Ions

The azimuthal velocity of the ions was measured for a series of operating conditions of the arc which were logged as data sets for \( Q = 5 \text{ ccNTP}, \ I = 100 \text{ A} \) and different values of the magnetic field, \( B \). The result of the automatic evaluation of the profiles after the deconvolution procedure is summarized in Fig. 6a, where \( \Omega \) is depicted as function of \( B \). The \( \Omega (B) \) curve, obtained directly from the profiles written by an XY recorder (thus without inversion) are shown in Fig. 6b for comparison.

The main source of errors in these measurements seems to lie in occasional displacements of the axis of the arc due to surface effects on the electrodes. Reference profiles taken at regular intervals of time show that the position of the axis generally wandered over a distance of 1 mm during the recording of a whole set of profiles i.e. in 20 - 30 minutes. This limits the precision of the measurement to 10 %. In general, the measurements made at the higher magnetic fields (6 kG) show a better stability of the arc and accordingly a smoother evolution of the vorticity profile. For this series of measurements, the central angular frequency increases with magnetic field up to \( B = 4,2 \text{ kG} \), and decreases slightly over this value.

3.4. The ion temperature was determined graphically from the profiles, recorded on a XY plotter. Fig. 7 shows \( T_i \) as function of the magnetic field, \( B \), before \( (I = 100 \text{ Amp, } \dot{J} = 4,5 \text{ ccNTP/sec}) \). For values of \( B > 1700 \text{ Gauss} \) the ion temperature does not vary
noticeably with the magnetic field; \( T_i \approx 3.5 \text{ eV} \). A brief series of recordings at an arc current \( I = 200 \text{ A} \) has shown that the ion temperature, \( T_i \), is about twice as high as for an arc current of 100 Amp. As expected theoretically the angular frequency, \( \Omega \), is increased approximately with the same factor (see Fig. 6b). By comparing values of \( T_i \) and \( \Omega \), obtained from measurements made under different arc conditions, it has to be kept in mind that by changing one parameter (e.g. \( I \)) some other intrinsic and extrinsic parameters in the arc may also change.

The emission of Ar I 4208 Å was about 10 times weaker than that of Ar II 4806 Å used generally. The rotation and temperature estimation from Ar I agrees with that of Ar II, from which we infer that Ar I is emitted by just recombined ions partaking of the same velocity distribution as the unbounded ones.
4. LANGMUIR PROBES MEASUREMENTS

4.1. Langmuir Probe Characteristics

Fig. 8 shows a drawing of the improved Langmuir Probe mount. Numerous probe characteristics were recorded for different probe geometries at various positions and under various arc conditions (arc current, I, gas flow, Q, and magnetic field strength, B). The cylindrical probes deteriorate faster in the presence of the arc than the flat probes, mainly because of deposition of cathode material on the insulating surface. Before the shield was mounted around the cathode, they could be used for about 15 minutes, with the shield for hours. The flat probes - simply made by mounting a circular disk on the probe tip last practically indefinitely.

Probe characteristics measured in the middle of the arc at a radial distance \( r = 4 \) cm are shown in Fig. 9a (at \( B = 1700 \) Gauss) and Fig. 9b (at \( B = 5100 \) Gauss). \( V_s \) is the voltage relatively to the anode, which is always at or about ground potential. Up to distances of 4 to 5 cm from the axis the ionic part of the characteristics is well reproducible, at larger radii the deviation between different recordings is considerably larger (Fig. 9c). The deviations in the electron saturation part of the characteristics is always found to be large. In view of these results we may confirm a conclusion which was reached before, i.e.; Langmuir Probe measurements yield reliable data of the plasma density and the floating potential (in our case up to \( r = 4-5 \) cm), but electron temperature and plasma potential cannot be measured very accurately with L.P. in the presence of a magnetic field. So far as electron temperature measurements may be trusted, it seems that the electron temperature in the outside regions (\( T_e \approx 2 \) eV) is much less than in the core region of the arc (\( T_e \gg T_i = 4 \) eV).
4.2. **Radial density profiles**, measured with a flat probe for three different values of the magnetic field strength, \( B \), are shown in Fig. 10a-c; cylindrical probes yield the same profiles. The relation between the ion saturation current to the probe and the plasma density is given by 
\[
I_s = \left( \frac{1}{4} \right) n e \bar{V} A.
\]

There is some uncertainty about the value to be taken for the mean ion velocity, \( \bar{V} \), and about the effective surface area, \( A \), of the probe. According to BOHM (1949) and later authors on this subject, e.g. CHEN (1965), 
\[
\bar{V} = \left( \frac{k T_e}{m_i} \right)^{1/2}
\]
the usual case that \( T_e > T_i \). In our case \( T_i \gg T_e \) and we may take for \( \bar{V} \) the thermal velocity of the ions:
\[
\bar{V} = \left( \frac{k T_i}{m_i} \right)^{1/2}.
\]
The radius of the flat probe is rather large (2.5 mm), but still smaller than the mean free path length (\( \lambda \approx 1 \text{ cm} \)) and comparable to the cyclotron radius of the Argon ions. Thus it seems reasonable to take for \( A \) the actual surface of the probe. Under these assumptions a probe current of 1 Amp corresponds to a plasma density, \( n \), of \( 2.8 \times 10^{14} \text{ part/cm}^3 \). As in the presence of a magnetic field the ion collection by the probe is not known exactly, the absolute value of the plasma density is only known within a factor of two.

The density profile may be measured up from a distance \( r = 2 \text{ cm} \); at closer distances to the centre the probe will glow and even melt. As the ion temperature does not change much with radius, the shape of the density profile at a certain value of \( B \) is measured properly. The profiles have clearly a Gaussian shape
\[
n = n_0 \exp \left( -\frac{r^2}{q^2} \right).
\]
\( q \) depends on \( B \) and may easily be calculated from the ratio of the \( n \) values measured at \( r = 2 \text{ cm} \) and \( r = 4 \text{ cm} \). For Fig. 10a-c we find respectively at \( B = 1700 \text{ Gauss} \): \( q^2 = 9.3 \text{ cm}^2 \); at \( B = 3400 \text{ Gauss} \): \( q^2 = 6.2 \text{ cm}^2 \) and at \( B = 5100 \text{ Gauss} \): \( q^2 = 4.2 \text{ cm}^2 \).

At a certain radius, \( r_K \), a more or less pronounced kink appears in the density profile and at radii larger than \( r_K \) its shape is no longer Gaussian. From this radial distance on the plasma appears to be turbulent, a surmise which is reinforced, by the fact that the ion collection current is not measured
reproducibly. In Fig. 10a-c this is indicated by two divergent lines between which the probe currents were found at different occasions.

4.3. The floating potential \( V_{\perp} \) (relatively to the anode) as function of radius for various values of \( B \) is shown in Fig. 11. The probe characteristics indicate that for \( r > 2 \text{ cm} \) the electron temperature does not change much any more with radius. Thus the radial electric field may be derived from Fig. 11 with sufficient accuracy to give some valuable information for the understanding of the behaviour of the plasma column. \( E_r = -\nabla V_{\perp} \)

points inward, which has to do with the tendency of the ions to move faster through the magnetic field than the electrons.

4.4. A directional Langmuir Probe rotating around an axis pointing in radial direction was used to measure azimuthal fluxes locally. Even if the plasma density, \( n \), is not known the azimuthal ion velocity, \( V_{i\theta} \), may be determined in this way. The problem of rotating the probe shaft in vacuum was solved by modifying the flange of the probe mount (Fig. 8) so that its inner part (connected to the probe) can be turned relatively to its outer part (mounted on the vacuum chamber).

The first measurements were made with a flat Platinum probe (\( \varnothing = 5 \text{ mm} \)), insulated at one side with glass. These probes which functioned properly in a low density plasma (BOESCHOTEN and SCHWIRZKE, 1962) failed in the hot and dense plasma of the vacuum arc, mainly because of melting of the glass. Therefore a probe construction of HUDIS and LIDSKY (1970) was used, which operated quite satisfactorily. Some results are shown in Fig. 13a and 13b, where the ion saturation current to the probe (\( V_S = -20 \text{ V} \)) is drawn as function of \( \varnothing \) for various values of \( B \). The directed part of the ion current, \( V_{i\theta} \), follows from the periodic changing part of curve, whereas the d.c. part of the curve corresponds to the isotropic part, \( i_S \), of the ion current (see

*) A drawing of this rotational Langmuir Probe is shown in Fig. 12.
section 4.2). \[ V_{i\phi} = \left( V_{it} / q \right) \left( \Delta i_s / i_s \right) \], where \( \Delta i_s \) is the difference between the ion saturation current collected when the plasma is streaming into the probe and when the plasma is streaming away from the probe. The determination of the azimuthal velocity with directional L.P. may be complicated by the presence of longitudinal ion fluxes, which cause a "phase" shift of the \((i_s, \psi)\) curves. Furthermore sheath effects manifest themselves in a still more complicated way than in usual probe theory. Nevertheless the values of \( V_{i\phi} \) found with the directional probe are in good agreement with the pendulum measurements, as may be seen in Fig. 16, where all results are depicted in one graph.

5. PENDULUM MEASUREMENTS

The rotation of the plasma body may be detected simply and directly with the aid of a small pendulum, suspended above the arc and electrically insulated from the wall (BOESCHOTEN and DEMETER, 1968). If \( G = mg \) is the weight of the pendulum and \( A \) its surface area, the rotational velocity of the ions, \( V_{i\phi} \), is related to the angle of deflection, \( \alpha \), by the relation:

\[ mg \sin \alpha = m_i \sin \theta V_{i\theta}^2 A \].

At small radii, where \( n_i \) and \( V_{i\theta} \) are large, a heavier vane must be used than further away from the axis. As Tungsten wires have the disadvantage of being stiff and are liable to melt close to the core region, an improved version of the original pendulums was used, which is shown in Fig. 14. The whole body is made out of thin Tantalum plate and is suspended in V shaped supports, like used in a balance. In this way the accuracy, the range and the ease of the measurements could be improved. For this geometry the left hand side of the equilibrium formula has to be divided by a factor of 2 if \( m \) is the total weight of the vane. Compared to thin wires the strips have the disadvantage of collecting more of the kinetic moment of the rotating plasma. But as the plasma density, \( n \), falls rapidly with radius the error introduced in this way is small and moreover it is compensated partly by other corrections.
The results of the measurements with two vanes of different weight are shown in Fig. 15, where \(\sin \alpha\) is depicted as function of the magnetic field strength, \(B\), for various values of radius \(r\). In Fig. 16 values of \(\Omega\) (\(\Omega = V_\phi / r\)) are shown which are calculated from Fig. 15. For these calculations the absolute value of the plasma density, \(n\), has to be known. These are taken from the L.P. data (see Fig. 10a-c of section 4.2). The statistical error is indicated by a bar, but the systematical error (because of \(n\)) may be much larger. It turns out, however, that the pendulum measurements are in good agreement with the directional L.P. measurements and that the joining to the Doppler shift measurements is also good.

6. COMPOSITION OF THE PLASMA ROTATION MEASUREMENTS

Fig. 16 is a composition of the measurements with the various diagnostic methods which are discussed in the previous paragraphs. It shows the angular frequency, \(\omega\), as function of radius, \(r\), for various values of the magnetic field strength, \(B\), for an Argon arc originating from a 15 mm diameter hollow cathode operated with an arc current of 100 Amp and with a gas feed of 4.5 ccNTP/sec. A positive (negative) \(\omega\) corresponds to the ion (electron) diamagnetic direction. The measurements with the interferometer, the pendulum and the directional L.P. fit nicely together. The shape of the curve differs from the \(\omega(r)\) curve of a H.C.D. plasma which was published earlier by BOESCHOTEN and DEMETER (1968) (Fig. 12 of that publication). The pendulum measurements, made at larger radii \((r = 3-4 \text{ cm})\) yielded the same results as mentioned in this report. But in the earlier work the direction of the plasma rotation in the core region, as derived from spectrographic measurements, must have been taken erroneously also in the ion direction instead of the electron direction. This mistake has no consequences for the analysis of the plasma behaviour at radius \(r = 4 \text{ cm}\) as was given in that publication, but it could have impeded a proper understanding of the behaviour of the whole plasma. Parts of \(\Omega(r)\) curves as found in H.C.D-es operating at
lower densities, \( n \), and magnetic field strength, \( B \), were published by ALDRIDGE and KEEN (1970), by HUDIS and LIDSKY (1970) and by TIELEMANS (1971).

In the arc core the plasma rotates in the direction of the electrons. In the plasma region next to it the rotational velocity decreases and even changes its direction. At larger radii the rotation is in the direction of the ions, reaches a maximum and approaches zero in the outer region of the arc. The maximum \((d\Omega/dr = 0)\) occurs closer to the axis for higher values of the magnetic field strength, \( B \), and its position corresponds within one or two millimeters (representing the accuracy in the positioning of the probes and the pendulum) with the place of kink in the \( n(r) \) curve. This arises the surmise that a rotational instability sets in at this place. A stability analysis which confirms this conjecture will be published soon. Extensive measurements of the spontaneous low frequency oscillations in the plasma, which were already planned for 1973, are recently started by D. KLEYN. Parallel to these measurements the theory of the rotational instability will be worked out to the extent that quantitative comparison with the experimental data will be possible.

In conclusion it may be noted that for a proper quantitative evaluation of the stability problem, the plasma density, \( n \), and the electron temperature, \( T_e \), have to be known more accurately than they are at this moment. The shape of the radial plasma density profile is known well enough, but the absolute value of \( n \) may be a factor of 2 off. In the core region \( T_e \) is expected to be at least equal to \( T_i \) \((\approx 4 \text{ eV for an Argon arc, when } I = 100 \text{ Amp and } Q = 4,5 \text{ cc NTP/sec})\). The L.P. measurements indicate that \( T_e \) falls strongly with radius - at least a factor of 2 between the core region and \( r = 3 \text{ cm} \). More precise information on \( n \) and \( T_e \) is expected from scattering experiments with laser light. The ion temperature, \( T_i \), is found to be constant with radius up to \( r = 3 \text{ cm} \). In order to measure \( T_i \) further away from the axis the sensitivity of the interferometric set up has to be improved.
7. APPENDIX

DIGITAL TREATMENT OF THE INTERFEROMETRIC DATA

7.1. Automatic Data Acquisition

According to the pressure scanning scheme, the recording of a spectral profile consists in a sequence of measurements of the parallel light throughput of the Fabry-Perot interferometer at increasing values of the air pressure (i.e. of the refractive index) between its plates. In our case, this is a two channel recording of

a) the signal X(t) of a pressure transducer (wavelength)

b) the signal Y(t) of a photomultiplier (light intensity),

where the pressure is swept over an interval of 0.4 Atm corresponding to 500 milliÅngströms in 5 to 10 sec.

Former measurements of the line shift and -broadening relied exclusively on the graphic comparison of profiles corresponding to different regions of the arc and drawn on the same record sheet of an XY recorder driven by the X(t), Y(t) signals.

During the more recent measurements the XY recorder was used merely as the real time display part of a more powerful digital data acquisition system using a 620f Varian process computer (see Fig. 17). For this purpose, the two measurement channels were also connected to the 620f over precision amplifiers and analog-to-digital converters. The process computer was programmed to store a sample of Y (intensity) every time X (wavelength) reached one of a sequence of levels. Typically, the profile corresponding to a given position across the arc was stored in memory in the form of 250 values of Y corresponding to so many linearly increasing values of X. The Y values were immediately logged in paper tape. Typically about 30 profiles corresponding to so many equidistant positions across the arc were measured and logged sequentially on the same paper tape. Concurrently, the profile at a standard position near the axis was logged repeatedly as a check of the stability of the arc.
A data set of 40 profiles, i.e. $10^4$ values of the intensity can be obtained for any operating condition of the arc i.e. for given arc current, gas supply, magnetic field etc. We shall call it in the following a "condition". A condition is thus logged on a 70 kbytes (8 bits-ASCII) paper tape. In view of a faster and safer accessibility, all conditions measured in the group to date have been copied onto a high capacity magnetic tape. This final data logging phase was performed on the B 6700 Burroughs computer of the THE*).

7.2. **Data Handling** (see Fig. 18)

The large amount of experimental data thus available deserved an exhaustive treatment using the computing capacity of the B 6700. Two consecutive ALGOL programs were specially developed for that purpose. The result of the second one is a reconstruction of the radial distribution of velocity and of the "true" emission profile at any radius.

The first program, called MAGROPLA mainly tailors the data set to the model of a rotation symmetric plasma column. According to that model, the profile emitted by any element of a plasma shell rotating around the axis should be Doppler-shifted of an amount depending only on its velocity towards the observer, i.e. on radius and angle. The shift should be opposite for the profile emitted by the diametrically adverse element. Now, considering the recordings corresponding to two lines of sight which are symmetrical about the axis, one sees that they can be decomposed in profiles due to symmetrical elements. Hence, the two recordings may be deduced from each other by a symmetry around the emission wavelength of an atom at rest. Accordingly, MAGROPLA

* We would like to express our thanks to J.W. Peters for writing the program for the 620f and to P.Th. Tutelaers for the batch transfer program on the B 6700.
selects the desired data set on the magnetic tape and transfers it to a matrix \( M(W, X) \) whereby \( W \) is the wavelength index and \( X \) the geometrical position index. After editing \( M(W, X) \), MAGROPLA determines its most probable center of symmetry \( C_W, C_X \) and performs a gross analysis of the profiles at \( X = \) constant, taking \( C_W \) as the wavelength at rest and \( C_X \) as the position of the axis. Finally it punches on a paper tape a combination of \( M \) with its symmetric about \( C_W, C_X \).

The second program, called ROTABEL, works on these symmetrised data. As already pointed out, every apparent profile recorded side-on at a certain distance of the axis is the superposition of all the profiles emitted by the volume elements encountered by the line of sight. ROTABEL has the task of reconstructing the true profiles from a sequence of apparent profiles taken at increasing distance from the axis. The procedure is a two-dimensional generalisation of Abel's inversion method and makes an extensive use of the Fast Fourier transformation. It will be dealt with in a separate publication.

Finally, the apparent and the true profiles are analysed and compared with each other. In both cases the results are tabulated and displayed in a synoptical listing like that of Table I.
REFERENCES

ALDRIDGE R.V. and KEEN B.E. (1970), Plasma Physics 12, 1

BASTIAN C., BOESCHOTEN F., HEKMAN H., KOMEN R., RISKE H.P. and

BOESCHOTEN F. and SCHWIRZKE F. (1962), Nuclear Fusion 2, 54

BOESCHOTEN F. and DEMETER L.J. (1968), Plasma Physics 10, 391

"Characteristics of Electrical Discharges in Magnetic

CHEN F.F. (1965), in Huddlestone R.H. and Leonard S.L. (Eds)
"Plasma Diagnostic Techniques", Academic Press,
New York


MINOG H. (1969), "Etude de Décharges à Cathode Creuse à Flux
de Gaz en Regime d'Arc", Orsay Rapport L.P. 94

TIELEMANS P.A.W. (1971), "Temperaturen en Rotaties van Argon-
onen en -atomen in een door een magnetisch veld
opgesloten plasma", T.H. Eindhoven-Report
Fig. 1  IMPROVED CATHODE ASSEMBLY
Fig. 2  IMPROVED ANODE ASSEMBLY
Fig. 3 MOVABLE ELECTRODE SUPPORT SYSTEM
Before Inversion

After Inversion

Fig. 5 Typical Results of the Automatic Deconvolution Procedure

- Before Inversion
- After Inversion

RADIAL POSITION IN MM

TOTAL LIGHT INTENSITY

LINE SHIFT IN MA

RADIAL POSITION IN MM

EUR-90-015
Fig 8  IMPROVED LANGMUIR PROBE MOUNT
Fig 9a LANGMUIR PROBE CHARACTERISTIC \( \cdot, x, o \) MEASUREMENTS ON SEVERAL DAYS EUR-90-019
Fig. 9b LANGMUIR PROBE CHARACTERISTIC \( r=4 \text{ cm} \), \( Q=4.5 \text{cc NTP/s} \), \( I=100 \text{ Amp} \), \( B=5100 \text{ G} \)

**Graph Details:**
- **Axes:**
  - **Vertical Axis:** \( I_S \text{(mAmp)} \)
  - **Horizontal Axis:** \( V_S \text{(Volt)} \)
- **Data Points:**
  - Various symbols and points indicating measurements taken on several days.

**Description:**
This graph illustrates the Langmuir probe characteristic measurements taken over several days with specified conditions of distance, flow rate, current, and magnetic field strength.
$r = 6 \text{ cm}$
$Q = 4.5 \text{ ccNTP/s}$
$I = 100 \text{ Amp}$
$B = 1700 \text{ G}$

Fig. 9c LANGMUIR PROBE CHARACTERISTIC \(\times, o, +\) MEASUREMENTS ON SEVERAL DAYS
\( B = 1700 \, \text{G} \)

\( I = 100 \, \text{Amp} \)

\( Q = 4.5 \, \text{cc NTP/s} \)

\( I_s = \text{CURRENT TO FLAT LANGMUIR PROB} \)
$B = 3400 \text{ G}$

$I = 100 \text{ Amp}$

$Q = 4.5 \text{ ccNTP/s}$

$I_s = \text{CURRENT TO FLAT LANGMUIR PROBE}$

Fig. 10b RADIAL DENSITY PROFILE
$B = 5100 \text{ G}$
$I = 100 \text{ Amp}$
$Q = 45 \text{ cc NTP/s}$

$I_s =$ CURRENT TO FLAT LANGMUIR PROBE

**Fig. 10c** RADIAL DENSITY PROFILE
$V_{fl}$ (Volt)

$I = 100$ Amp
$Q = 4.5$ ccNTP/s

$B = 1700$ G
$B = 3400$ G
$B = 5100$ G

Statistical Error

Fig. 11 FLOATING POTENTIAL AS FUNCTION OF RADIUS
FOR VARIOUS VALUES OF B

EUR-90-025
Fig. 12 DIRECTIONAL LANGMUIR PROBE MOUNT
Fig. 13 DIRECTIONAL CURRENT TO LANGMUIR PROBES
AS FUNCTION OF ANGLE $\theta$

$\mathbf{a}$

$I = 100$ Amp
$Q = 4.5$ cc NTP/s
$r = 3.5$ cm

$B = 1700$ G
$B = 3400$ G
$B = 5100$ G

$l_s$(arb. un.)

30 60 90 120 150 180 210 240 270 300 330 360 \(\theta\) (degrees)

$\mathbf{b}$

$I = 100$ Amp
$Q = 4.5$ cc NTP/s
$r = 4$ cm

$B = 1700$ G
$B = 3400$ G
$B = 5100$ G

$l_s$(arb. un.)

30 60 90 120 150 180 210 240 270 300 330 360 \(\theta\) (degrees)
Fig. 14 IMPROVED PENDULUM
Fig. 15 DEFLECTION OF PENDULUM OF DIFFERENT WEIGHT AS FUNCTION OF RADIUS r

I = 100 Amp
Q = 45 ccNTP/s

B (560 G)

Pendulum III (1391 mg)

Pendulum II (616 mg)
Fig. 16 ROTATIONAL FREQUENCY AS FUNCTION OF RADIUS
Interferometric Setup (schematic)

Photo Multiplier (I)

Pressure transducer (λ)

Interferogram

XY Recorder
Real-time supervision

Precision Amplifiers

VARIAN 620f process computer

Punch TAPE

Teletype (Control)

Intermediate Log (1 paper tape per condition)

PAPER TO TAPE
(Algol Program)
B 6700

MAGNETIC TAPE LOG

Final Log

ROTAING PLASMA SPECTROSCOPY

FIG. 17 DATA ACQUISITION & STORAGE
MAGNETIC TAPE LOG (Raw D. S.)

B 6700 / SUMMARY
Selects & Punch
Data Set headings

D.S. heading
SELECTION DECK

SYMMETRISED D.S. (INTERMEDIATE LOG)

B 6700 / ZOFUPROG
Computes Zonal Functions

B 6700 / MAGROPLA
Selects and Symmetrize D.S.

B 6700 / ROTABEL
Generalised Abel Inversion in Fourier Space

COARSE REPORT
Edition & Analysis of the Raw Data Sets

PAPER TAPE
1 Paper Tape per D.S.

FINAL REPORT
Edition & Analysis of the Profiles before and after Inversion

ROTATING PLASMA SPECTROSCOPY

FIG.18 DATA TREATMENT
TABLE I

<table>
<thead>
<tr>
<th>MEAN RADIUS</th>
<th>LINE CENTER</th>
<th>R.M.S. SPREAD</th>
<th>GLOBAL INTENSITY</th>
<th>KIN+ENERGY TO THERMAL</th>
<th>ASYMMETRIC PART (dB)</th>
<th>BACKGROUND NOISE (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.5</td>
<td>27.0</td>
<td>3.25*10^05</td>
<td>3.06*10^-03</td>
<td>-23.1</td>
<td>-22.5</td>
</tr>
<tr>
<td>1.5</td>
<td>0.0</td>
<td>27.1</td>
<td>3.07*10^05</td>
<td>4.06*10^-02</td>
<td>-23.5</td>
<td>-21.7</td>
</tr>
<tr>
<td>2.5</td>
<td>9.5</td>
<td>27.3</td>
<td>2.08*10^05</td>
<td>1.21*10^-01</td>
<td>-25.3</td>
<td>-22.0</td>
</tr>
<tr>
<td>3.5</td>
<td>12.0</td>
<td>27.4</td>
<td>2.10*10^05</td>
<td>1.55*10^-01</td>
<td>-19.9</td>
<td>-20.6</td>
</tr>
<tr>
<td>4.5</td>
<td>13.5</td>
<td>29.3</td>
<td>1.44*10^05</td>
<td>2.12*10^-01</td>
<td>-17.5</td>
<td>-20.2</td>
</tr>
<tr>
<td>5.5</td>
<td>13.0</td>
<td>42.0</td>
<td>1.02*10^04</td>
<td>1.63*10^-01</td>
<td>-15.1</td>
<td>-17.7</td>
</tr>
<tr>
<td>6.5</td>
<td>10.0</td>
<td>36.1</td>
<td>5.43*10^04</td>
<td>7.00*10^-02</td>
<td>-15.9</td>
<td>-15.4</td>
</tr>
<tr>
<td>7.5</td>
<td>6.5</td>
<td>39.4</td>
<td>3.70*10^04</td>
<td>2.00*10^-02</td>
<td>-15.1</td>
<td>-13.8</td>
</tr>
<tr>
<td>0.5</td>
<td>4.0</td>
<td>41.6</td>
<td>2.69*10^04</td>
<td>9.10*10^-03</td>
<td>-19.0</td>
<td>-14.1</td>
</tr>
<tr>
<td>4.5</td>
<td>3.0</td>
<td>43.4</td>
<td>2.63*10^04</td>
<td>4.06*10^-03</td>
<td>-19.6</td>
<td>-13.4</td>
</tr>
<tr>
<td>7.5</td>
<td>2.5</td>
<td>46.1</td>
<td>2.04*10^04</td>
<td>2.16*10^-02</td>
<td>-17.0</td>
<td>-11.4</td>
</tr>
<tr>
<td>12.5</td>
<td>2.0</td>
<td>47.5</td>
<td>1.75*10^04</td>
<td>1.70*10^-02</td>
<td>-17.0</td>
<td>-11.4</td>
</tr>
<tr>
<td>13.5</td>
<td>2.5</td>
<td>40.6</td>
<td>1.57*10^04</td>
<td>2.64*10^-03</td>
<td>-17.5</td>
<td>-10.7</td>
</tr>
</tbody>
</table>