The vacuum ARC as a facility for relevant experiments in fusion research

Citation for published version (APA):
Bastian, C., Boeschoten, F., Hekman, H., Komen, R., Riske, H. P., & Iersel, van, A. W. M. (1973). *The vacuum ARC as a facility for relevant experiments in fusion research*. (EUT report. E, Fac. of Electrical Engineering; Vol. 73-E-35), (EURATOM - THE Group "Rotating Plasma" : annual report; Vol. 1972). Technische Hogeschool Eindhoven.

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: 21. May. 2024

THE VACUUM ARC AS A FACILITY FOR RELEVANT EXPERIMENTS IN FUSION RESEARCH

ANNUAL REPORT 1972

EURATOM - THE Group "Rotating Plasma"

TECHNISCHE HOGESCHOOL EINDHOVEN
NEDERLAND
AFDELING DER ELEKTROTECHNIEK
GROEP ROTEREND PLASMA

EINDHOVEN UNIVERSITY OF TECHNOLOGY
THE NETHERLANDS
DEPARTMENT OF ELECTRICAL ENGINEERING
GROUP ROTATING PLASMA

THE VACUUM ARC AS A FACILITY FOR RELEVANT EXPERIMENTS IN FUSION RESEARCH

ANNUAL REPORT 1972

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 73-E-35
February 1973
ISBN 90 6144 035 1

THE VACUUM ARC AS A FACILITY FOR RELEVANT EXPERIMENTS IN FUSION RESEARCH

EURATOM - THE Group "Rotating Plasma"

ABSTRACT

The regime of plasma parameters in the high vacuum arc at Eindhoven "John S. Luce" is such that relevant experiments for fusion research may be done - particularly in the disregarded field of plasma rotation. It is a considerable advantage of this facility that it has a simple and variable geometry and is operated in the stationary state.

A description of the apparatus is given in section 3. The available diagnostic tools - section 4 - are laid out in such a way that the plasma rotation and the related turbulent phenomena may be measured adequately. The experiments were started in February 1973 and some of the first results are given in this report.

CONTENTS

1. INTRODUCTION

It is generally accepted that a proper confinement of a fusion plasma can only be realized in a toroidal geometry. But as this goal is not achieved yet and the plasma is lost by unknown reasons, it is still recommendable to study the behaviour of a plasma in a simple linear geometry with straight magnetic field lines. In order to obtain relevant data from these experiments, at least the following five conditions must be fulfilled:

1) The plasma must be fully ionized and relatively pure,
2) The plasma radius must be many (at least 10) ion gyro radii wide and smaller than the radius of the containing wall ($R > r_{pl} \gg r_{ci}$),
3) The plasma must be fully magnetized, i.e. the plasma particles must make many gyrations in the magnetic field before they collide with other type of particles or with each other ($\omega_{ci}\tau_i \gg 1$),
4) The ion Debye length must be small compared to the plasma radius ($r_{pl} \gg \lambda_{Di}$) and
5) The ratio of the plasma energy density to the energy density of the magnetic field must be non vanishing ($\beta > me/mi$).

Until now the only linear configurations which meet these requirements are the Θ pinch and the vacuum arc. The Θ pinch has a high temperature ($T_i \simeq 300$ eV) and density ($n \simeq 10^{16}$ part/cm^3) but exists only for a short time ($\tau \simeq 10^{-5}$ sec). The vacuum arc has a lower temperature ($T_i \simeq 10$ eV) and density ($n \simeq 10^{14}$ part/cm^3) but has the advantage of continuous operation, which makes experiments much simpler and cheaper.

2. IMPORTANCE OF PLASMA ROTATION

Plasma rotation is an important aspect of plasma physics which generally has been unjustly neglected. Much theoretical work starts from equations (see e.g. SPITZER, 1956) which do not describe adequately the stationary behaviour of a fully ionized plasma in a magnetic field as they imply a scalar plasma pressure, which does not pay a proper tribute to some determinative rotational phenomena. Several experiments which were started fifteen years ago with rotating plasma devices relied erroneously on the possibility to impose from the outside an electric field on the plasma and were stopped after some years of disappointments. All of this lead to a regrettable neglect of the importance of the intrinsic rotation of a plasma for the stability of a plasma confined by a magnetic field and for the transport of plasma particles across the magnetic field.

2.1. Influence of rotation on the stability of the plasma

Usually the plasma pressure is supposed to be a scalar, but in reality the stress tensor has quasi viscous terms which are proportional to the third space derivative of the density (see e.g. CHAPMAN and COWLING 1953). This makes that at larger radii the plasma is in a non uniform rotation. The shear in the azimuthal velocity leads to an instability which was found by ROSENBLUTH, KRALL and ROSTOCHER (1961) and which is distantly related to the Helmholz-Kelvin instability in hydrodynamics. Thus, over a certain radius ($r \gtrsim q^2/r_{ci}$; q is e-folding length of the density) the ion motion becomes turbulent. As the occurrence of this instability seems inevitable in all plasma configurations, its closer study is of great importance. A better understanding of this instability may lead to improved confinement schemes. Moreover the part played by the electrons in a weakly turbulent ion fluid is not clear. It may be expected that drift oscillations as first described by BOHM (1949) play a very important role.

2.2. Influence of rotation on the diffusion of plasma across the magnetic field

For a collisional, but still fully magnetized plasma ($\omega_{ci}\tau_i \gg 1$, but finite) the shear in the azimuthal velocity leads to a radial transport of the ions, which is determined by the ion-ion collision time (SIMON 1955). The transport rate may be much larger than the "classical" diffusion, which is determined by collisions between ions and electrons. Again the question arises whether an ambipolar electric field will be built up or whether the electrons may follow by drift oscillations.

2.3. Origin of the rotation

One may distinguish between two extreme situations: I, where the diamagnetic current is carried equally by ions and electrons (electrostatic E field $E_{e.s.} = 0$) and II, where the diamagnetic current is carried by the electrons alone ($E_{e.s.} \simeq (K\ T/e)\ (\nabla n/n)$). The R.K.R. stability criterion allows only radial electric fields $0 \lesssim E_{e.s.} \lesssim \frac{KT}{e}\ \frac{\nabla n}{n}$, for other values of $E_{e.s.}$ the plasma is rotationally unstable.

Which situation will occur depends on the way the plasma particles are generated. Case I can occur only if the plasma receives angular momentum from the part of the machine where it is generated, e.g. by reaction with the walls. The vacuum arc with $r_{ci}/q \ll 1$ and $\omega_{ci}\tau_i \gg 1$ and the Θ pinch with parallel trapped magnetic field represent examples of case I. One may conjecture that if the plasma is in contact with the wall at the time of its generation, it will rotate as described in case I.

To find an answer to the problem of how the plasma comes to a certain guiding centre distribution is at least as important as finding theoretically a certain equilibrium configuration, particularly if this is done with inadequate equations.

2.4. Drift instabilities

Drift oscillations are low frequency oscillations ($\omega_* < \omega_{ci}$) which arise from the radial drift of ions along the density gradient. For small longitudinal wave numbers ($\omega \ll K\, C_A$) the azimuthal phase velocity is equal to the diamagnetic drift velocity of the electrons. Under certain conditions these oscillations may lead to instability of the electron fluid. A comprehensive study of these ideas which were firstly posed by BOHM (1949) may be found in a book of KADOMSTEV (1965).

In a "collisionless" plasma the instability arises from the interaction between the drift waves and the resonant particles represented by Landau damping. (The transition from collisional to collisionless dissipation occurs at $\lambda_e K_z \simeq 1$). Long wave length perturbations ($K_\perp r_{ci} \ll 1$) are unstable only in the presence of a longitudinal current, the growth rate being given by $\gamma \simeq \sqrt{\pi}\, \omega_* (u/V_{et})$ - independent on L and M and dependent on the longitudinal current I. Short wave length perturbations ($K_\perp r_{ci} \gtrsim 1$) may be classified among Finite Larmor Radius effects. For $K_\perp r_{ci} \simeq 1$ the frequency reduces to $\omega_+ = 0.3\, \omega_*$ and the growth rate to $\gamma \simeq 3.10^{-3}\, \omega_*$, both depend strongly on M. Furthermore, the growth rate decreases with decreasing L, so that for $L \lesssim 30\, r_{pl}$ no drift instabilities should occur. Finally it depends on β , its effect becomes noticeable for $\beta \gtrsim m_e/m_i$.

The plasma of the vacuum arc cannot be considered collisionless in the sense that $\lambda_e K_z \ll 1$. Collisions between the particles may lead to instabilities of the drift-dissipative type. However, in a strongly ionized plasma with $r_{pl} \gg r_{ci}$ the drift instability is not much affected by collisions and its characteristics are qualitatively the same as in the collisionless case.

Drain diffusion. In the presence of drift oscillations the plasma moves across the magnetic field. If the amplitude of these oscillations increase with time, then each succeeding halfperiod of the oscillations leads to a slightly greater displacement of the plasma than the previous one and as a result a mean plasma flux in the direction of ∇ n occurs. In the case of weak turbulence ($\gamma \ll \omega$) this leads to a diffusion coefficient $D_\perp \approx \left< \gamma_K^2 / \omega K_\perp^2 \right>_{\max.}$ This kind of turbulent diffusion was called "drain diffusion" by BOHM, who found an expression $D_\perp = 10^8/16 \times Te/B$ for the diffusion coefficient of the electrons. Since the work of KADOMSTEV and others the theoretical understanding of this kind of turbulent transport has improved considerably. He found various expressions of $D_\perp$, depending on the different plasma parameters (β, L, u/V_e, M). As these parameters may be varied easily in the vacuum arc, it is very well suited for the study of drain diffusion. The necessary equipment - Correlator and Spectrum Display - is also present.

A situation of particular interest occurs when the ions are in "hydromagnetically" turbulent motion and the electrons follow by drain diffusion. In that case the drain diffusion should reach its maximum value. It can be shown in two different ways (TAYLOR 1961; BOESCHOTEN 1972) that this maximum value is given by the Bohm coefficient $D_\perp$ (BOHM).

3. DESCRIPTION OF THE APPARATUS

A picture of our machine is shown in Fig. 1. It is called John S. Luce, after the inventor of the vacuum arc (1958). Later on big arcs of this type were described by GIBBONS and MACKIN (1961) and by CANO et al. (1965). Smaller ones are operated at MIT (LIDSKY et al. 1962, WOO and ROSE 1967) at Orsay (DELCROIX et al. 1968) and at TH Eindhoven (VAN DER SIJDE 1969).

A schematic of the device is shown in Fig. 2. The vacuum chamber, the diffusion pumps, the magnetic field coils and the electrodes are suspended separately in a frame and may be rolled on wheels in horizontal direction. This construction allows an easy mounting and dismounting of the machine. The stainless steel vacuum chamber consists of three or four identical sections which are isolated from each other by means of teflon rings. Each section has four port holes with quartz windows (Ø = 138 mm).

The pumping system is shown schematically in Fig. 3. The diffusion pumps (12000 l/s) which are installed at both sides of the vacuum chamber are backed by rotary pumps (100 m^3/hr). An extra unit consisting of a Roots pump (1000 m^3/hr) and rotary pump (100 m^3/hr) has a double function: 1) as a roughing unit when the pressure in the chamber is over 0.1 Torr and 2) as a backing unit when the diffusion pumps are working and pressure in the chamber is over 10^{-5} Torr. The whole vacuum system is controlled automatically. The neutral gas pressure in the vacuum chamber is $1.5 \cdot 10^{-3}$ Torr. Due to the strong pumping action of the arc, the pressure lowers to half this value during operation. Vacuum conditions may be improved further by differential pumping, but till now this was not put into practice.

The solenoid creating the magnetic field is divided in units of each four elementary coils (Garching Instruments) stacked together in a wooden housing. These units are separately cooled with water and suspended in the frame at equal distance from one other. Normally two of these units are placed symmetrically on both sides of the portholes of each section of the vacuum chamber. The magnetic field may be adjusted between 500 and 6000 Gauss in continuous operation and up to 9000 Gauss during 15 sec. 1 Amp current corresponds to 5,75 Gauss inside the coils. The dependence of the magnetic field strength on radius is shown in Fig. 4.

The two electrode-carriers are movable which allows variation of the arc length during operation from 0 to 2500 mm. The anode and the cathode are isolated from the vacuum chamber and connected to a d.c. power supply (max current 500 Amp). The vacuum pumps are grounded. During operation the anode acquires about earth potential (0.1 V) and the cathode becomes negative. When the arc is operated at B = 1200 Gauss, Q = 5,5 ccNTP/sec and I = 100 Amp the sections of the vacuum chamber float to the following potentials: 3,2 V (section at the anode side), 40 mV (section in the middle) and 150 mV (section at the cathode side). If grounded the currents to the sections are respectively 600 mA, 20 mA and 200 mA.

These values decrease drastically if the magnetic field strength B is increased. At B = 4800 Gauss the currents to the grounded sections are a hundred times less, which gives a direct demonstration of the improved radial confinement of the plasma at higher values of B.

The arc is ignited with a h.f. discharge between the electrodes.

The cathode tube is mounted in a water cooled block made of copper, which is protected by a tungsten plate. The tubes for gas feed and water cooling are accomodated in a stainless steel carrier (Fig. 5). The cathode tubes used until now have internal diameters of 19 mm and 13 mm and a total length of respectively 170 mm and 120 mm. As the active zone of the cathode travels inwards at decreasing gas feeds, the tube must be made longer at low gas feeds.

Fig. 6 shows two current-voltage characteristics of the discharge for two different values of the gas feed: Q = 5,5 ccNTP/sec and Q = 2,75 ccNTP/sec.

4. DIAGNOSTICS

The rotational velocity of the plasma about its axis $V_\varphi(r)$ is measured spectroscopically from Doppler shifts of spectral lines. Further indications of $V_\varphi(r)$ are obtained from directional Langmuir probes and from the deflection of a pendulum.

The ion temperature (T_i) follows from the Doppler broadening of spectral lines, the electron temperature (T_e) from relative intensities.

The electron density distribution $n(r)$ of the plasma will be measured by Thompson scattering of laser light. Langmuir probes give a reasonable indication of $n(r)$ in the outer regions of the arc.

The fluctuating electric fields and densities in the plasma will be measured with a real time correlator completed by a Fourier transforming spectrum display.

4.1. Optical spectroscopy

The lower limit of the ion velocities to be measured is about 10^5 cm/sec and corresponds to a spectral displacement of about $2 \cdot 10^{-2}$ Å. Since the resolution requirements are easily met by an interferometric system without special refinements, we selected a pressure-scanned Fabry-Perot interferometer of moderate resolution and high luminosity to analyse the emission lines of the ions.

a. Optical layout (see Fig. 7)

The arc is observed from below through any of the lower ports of the vacuum vessel (see Fig. 2). The quartz window has a useful diameter of 138 mm and does not limit the radial range of observation.

The light emitted downwards from a given point A of the horizontal median plane of the arc is transformed into a vertical parallel beam by the objective lens L 1 and further deflected 90° by the prism P into a horizontal parallel beam perpendicular to the axis of the arc. L 1 and P are both mounted on a sliding table, and can be translated ± 60 mm in the direction of the horizontal output beam, i.e., perpendicular to the axis of the arc.

Consequently, the beam of parallel light under study comes from a point A of the horizontal median plane; the radial position of A can be set precisely with the micrometer screw of the sliding table without changing the further imaging characteristics of the output beam.

The optical bench is placed about 1200 mm below the vacuum vessel and perpendicular to its axis. Besides L 1 and P, the light beam passes on its way down the optical bench: first the Fabry-Perot interferometer, then the ocular lens L 2 which refocusses it into an image of the point A on the entrance slit of the monochromator. A photomultiplier flanged on the exit slit of the monochromator monitors the light output.

The focal lengths of L 1 and L 2 are 600 and 200 mm respectively, the horizontal entrance slit of the monochromator is usually 1 mm x 0.1 mm, so that the median plane of the arc can be scanned radially over ± 60 mm in strips of 0.3 mm radial x 3 mm longitudinal extent.

b. Interferometric system

The Fabry-Perot, with a useful diameter of 55 mm, analyses nearly the whole cross-section of the oncoming parallel beam. The multilayer coating of the plates ($\lambda/120$, Halle) is devised for maximal reflectivity between 4500 and 4800 Å. The original mounting has been replaced by a special construction following RUSBLÜDT-KOHLHAAS (KFA-IPP Jülich) which fits in a pressure-tight container and allows adjustment in the pressurized state.

The detection occurs at the center of the ring system in the focal plane of L 2. Typically, a new order of interference is attained for an increase in pressure of 0.8 kg/cm^2 N_2 in the F.P. container (1 mm spacing, λ = 4800 Å). Under the same conditions the free spectral range is 1.15 Å.

The grating monochromator has a focal length of 25 cm and an aperture of f : 4.5. With slits of 100 microns its resolution is 3 to 4 Å. The lines under study are chosen sufficiently distant from their next neighbours in order to prevent any overlapping of different orders.

The pressure in the F.P. container is continuously monitored by an inductive transducer actuating the X-sweep of a XY recorder, whereas the photometric signal actuates the Y motion. In this way a recording of the line profile can be obtained within a few seconds.

The instrumental profile of the interferometric system was determined using the 4800 Å line of a Cadmium lamp(line width: 10 mÅ). The width of the recorded profile was 85 mÅ. Under the same conditions, the maximal shift in wavelength over and below the midpoint of the free spectral range corresponds to an ion velocity of $\pm 3.6 \times 10^6$ cm/sec. For comparison the thermal velocity of an Argon ion at 10 eV is 8.65×10^5 cm/sec.

c. Results

The profile of Ar^{II} 4806 Å has been systematically recorded at different radial positions with either directions of the guiding magnetic field. Fig. 8 is a graph of the position of the center of the profile as a function of the radius of observation (displacement of the sliding table, see Sec 4.a.). The ordinates are given in units such that 1 cm (vertical) on the graph corresponds to a shift of 28 mÅ.

A true quantitative exploitation of the results would involve backwards convolutions to compensate for the own profile of the interferometric system and for the cylindrical geometry (Abel's transformation). These refinements will be made accessible in the near future with the help of a process computer.

Nevertheless it can be said with certainty that the plasma rotates in the same direction as the electrons for the following arc conditions:

Magnetic field strength B = 1800 Gauss
Arc current I = 100 A
Gas feed Q = 1.75/3.5 ccNTP/sec

As apparent on Fig. 8 the sense of rotation changes with the polarity of the magnetic field. The maximum azimuthal velocity is about 2×10^5 cm/sec at a radius of 8 mm, equal to the inner radius of the cathode. Within this radius, the rotation does not seem to depart markedly from uniformity whereas it falls rapidly at the outside. The line profiles had a halfwidth of about 160 mÅ, which would indicate an ion temperature of about: 8.7 eV.

4.2. Langmuir Probes

The extent to which Langmuir Probes may yield meaningful results in a magnetized plasma is a delicate question. So far there is no reliable theory available, the results being dependent on too great a many of parameters and assumptions. In general one may state that reasonable trustworthy (within a factor 1.5) information about the ion density may be obtained from ion saturation currents to the probe. The electron temperature T_e is determined roughly within a factor 2, but the plasma potential cannot be determined with the required accuracy ($\kappa T_e/e$). Disc shaped probes insulated at one side may be used to obtain information about the plasma rotation. For this purpose also ballistic measurements with a pendulum will be made (BOESCHOTEN and DEMETER, 1968).

Additionally the Langmuir probes pick up drift oscillations, both in the electric field and in the density. For this purpose they must be carefully designed in order to make sure where the oscillations are located. The construction of the probe is illustrated in Fig. 9. As pointed out in section 2 we expect the plasma to be turbulent in its outer regions, where the detection of drift oscillations is relatively easy.

REFERENCES

BOESCHOTEN F. and DEMETER L.J. (1967), Plasma Physics 10, 391

BOESCHOTEN F. (1972), TH Eindhoven Rep. 72-E-28

BOHM D. (1949), in Guthrie A. and Wakerling R.K. (Eds) "Characteristics of Electrical Discharges in Magnetic Fields", Mc Graw-Hill, New York

CANO R., MATTIOLI M., and ZANFAGNA B. (1965), Fontenay Rep. EUR-CEA-FC-312

CHAPMAN S. and COWLING T.G. (1953), "The Mathematical Theory of Non-Uniform Gases", Cambridge

DELCROIX J.L., MINOO H., and TRINDADE A.R. (1968), Rev.Roum. Phys. 13, 401

GIBBONS R.A. and MACKIN R.J. (1961), Proc. 5th Int.Conf. Ionization Phenomena in Gases, Munich, 1961

KADOMSTEV B.B. (1965), "Plasma Turbulence", Academic Press

LIDSKY L.M. et al. (1962), J. Appl.Phys. 33, 2490

LUCE J.S. (1958), Proc. 2nd U.N.Conf.Peaceful Uses Atomic Energy, 31, 305

ROSENBLUTH M.N., KRALL N.A., and ROSTOCKER N. (1961), Proc. Conf. Plasma Phys. Controlled Nucl. Fusion Res., Salzburg, 1961, Nucl. Fusion Suppl. 1, p. 143

SIMON A. (1955), Phys.Rev. 100, 1557

SPITZER L. (1956), "Physics of Fully Ionized Gases", Interscience

TAYLOR J.B. (1961), Proc. Conf. Plasma Phys. Controlled Nucl. Fusion Res., Salzburg, 1961, Nucl. Fusion Suppl. 2, 477

VAN DER SIJDE B. (1969), Proc. 9th Int. Conf. Ionization Phenomena in Gases, Bucharest, 1969,

VAN DER SIJDE B. (1972). J. Quant. Spectroc. Rad. Tr. 12, 703

WOO J.C. and ROSE D.J. (1967), Phys. Fluids 10, 893

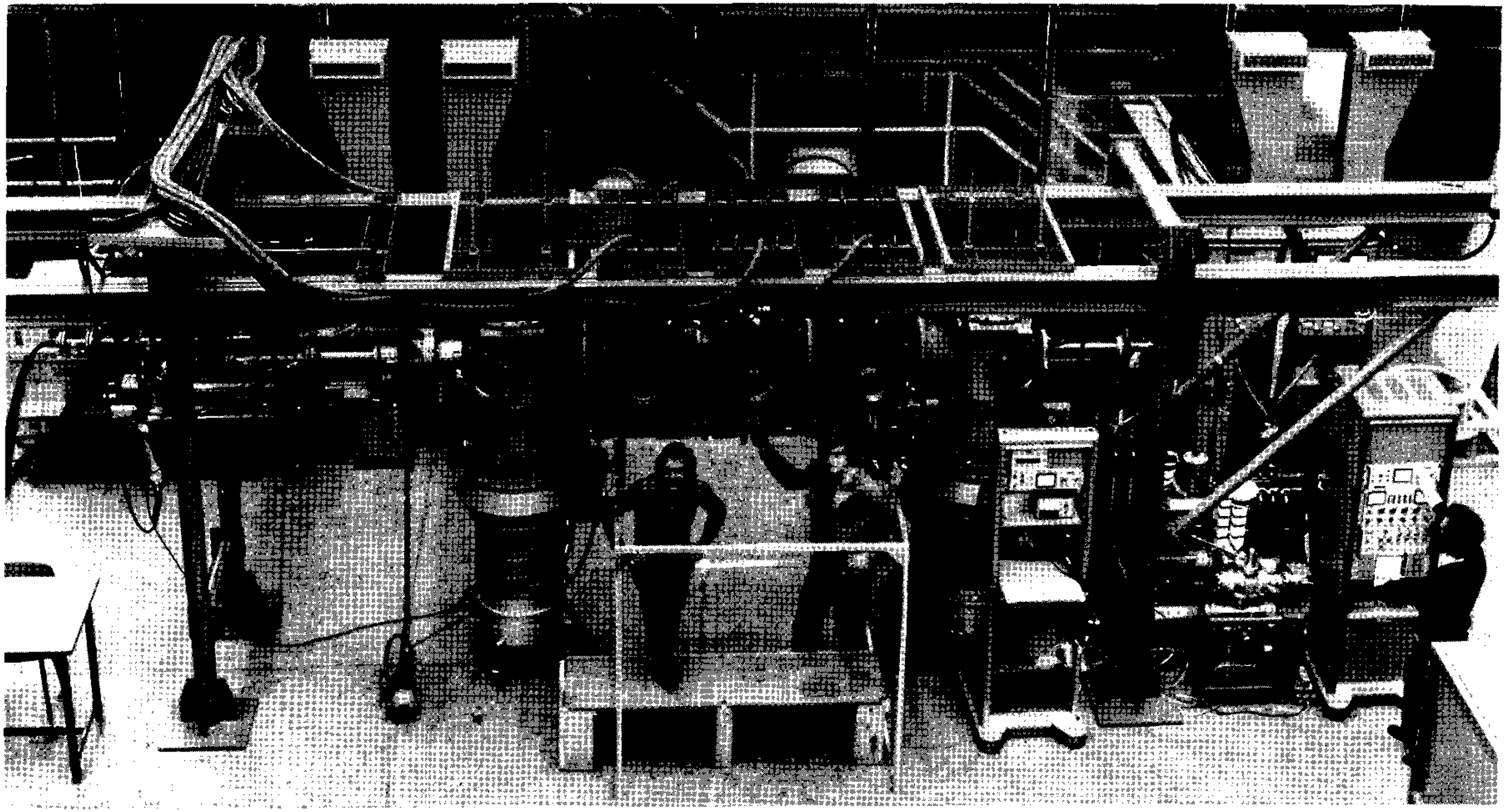
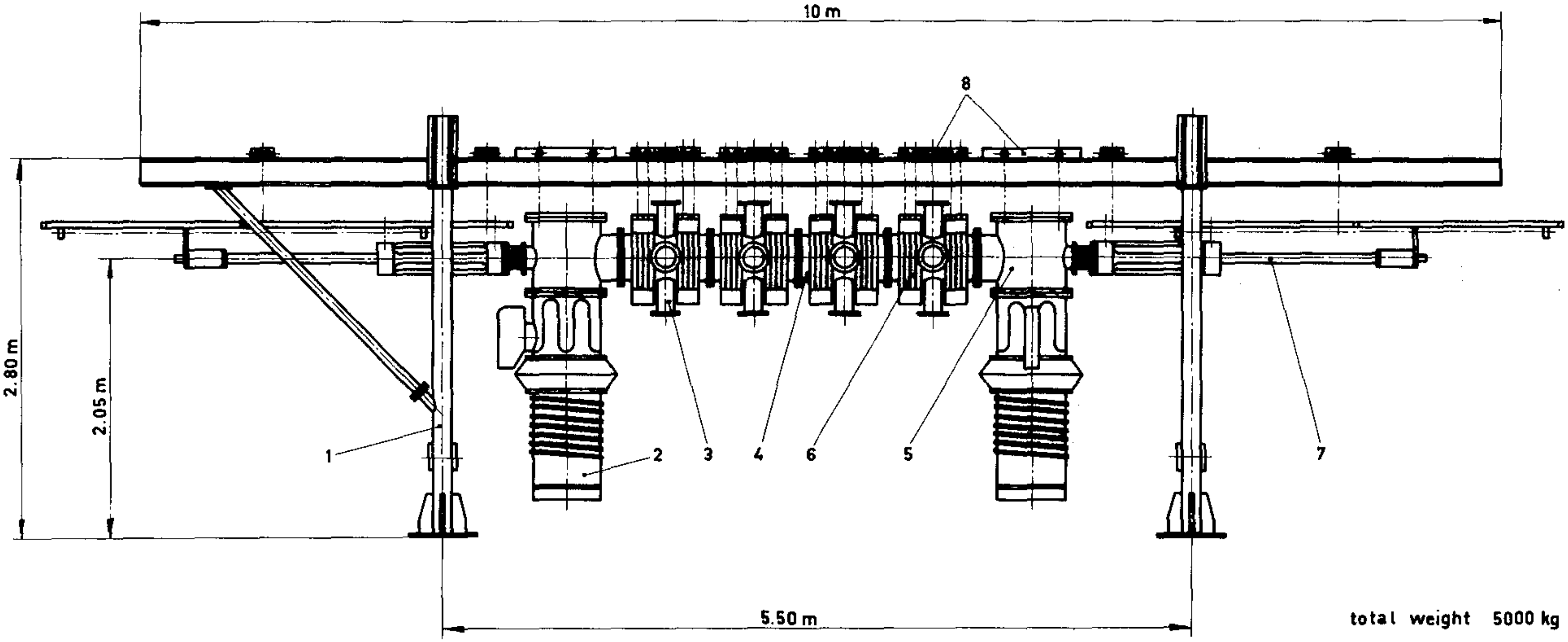


FIG. 1



total weight 5000 kg

FIG.2 GENERAL LAYOUT OF VACUUM ARC JOHN S. LUCE

8. Caets
7. Electrode
6. Magnet coils
5. Connection to pump
4. Section (electrically isolated)
3. Vacuum chamber
2. Diffusion pump
1. Frame

EUR - 90 - 002

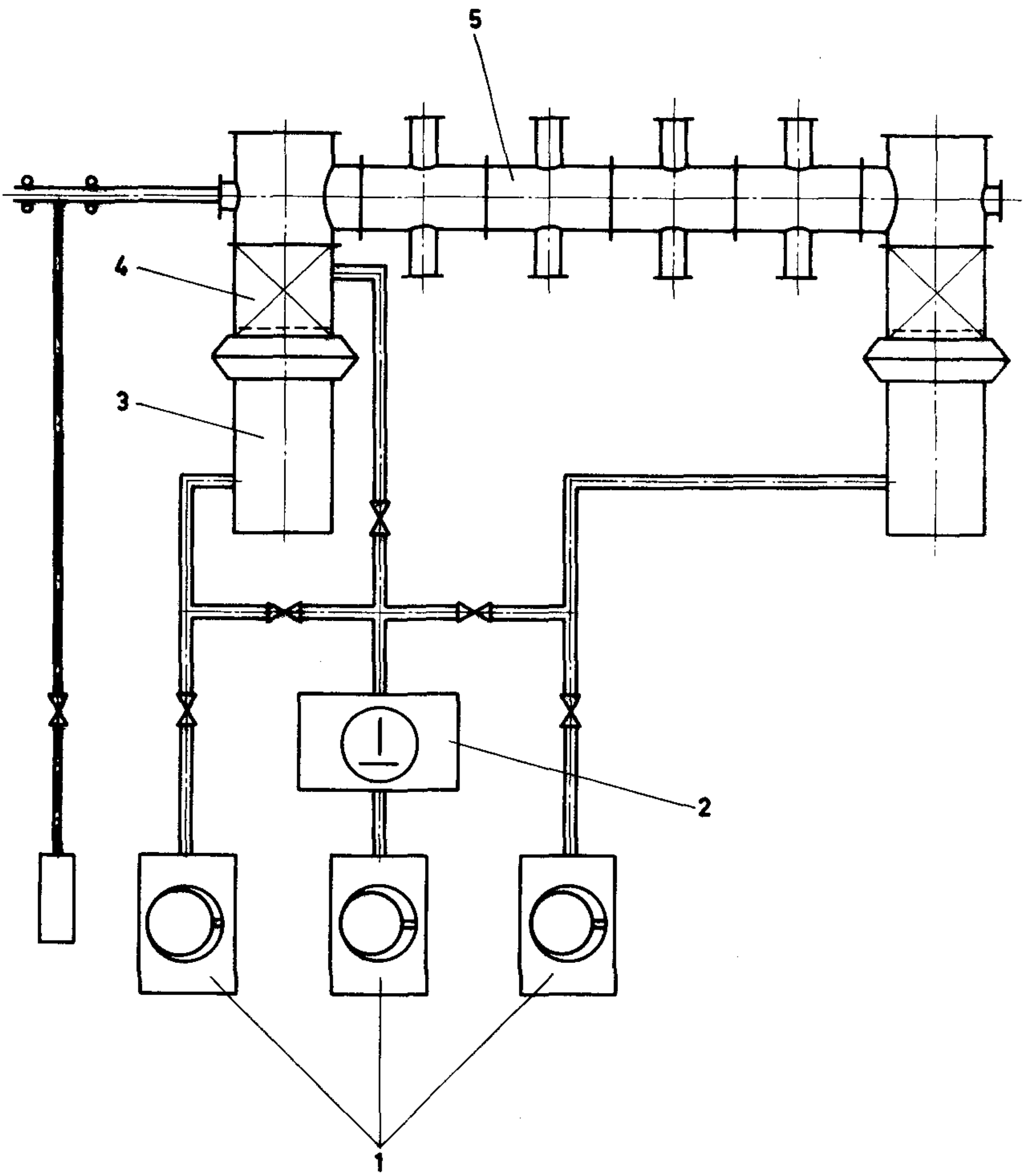


FIG.3 PUMPING SYSTEM

1. Rotary pumps (100 m^3/ h)
2. Roots pumps (1000 m^3/ h)
3. Diffusion pumps (12000 l /s)
4. Vacuum valve
5. Vacuum chamber

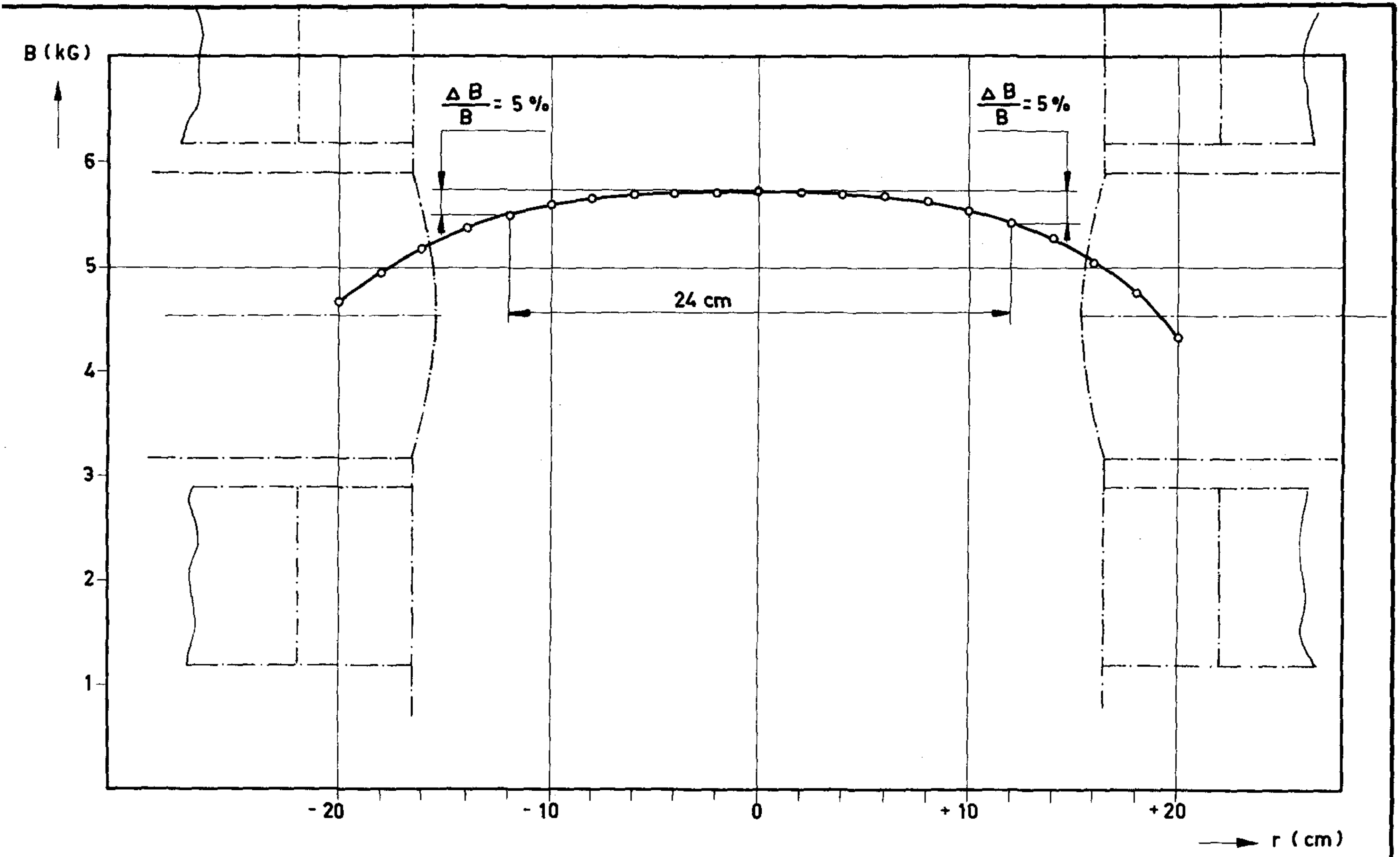


FIG.4 RADIAL DEPENDENCE OF MAGNETIC FIELD STRENGTH

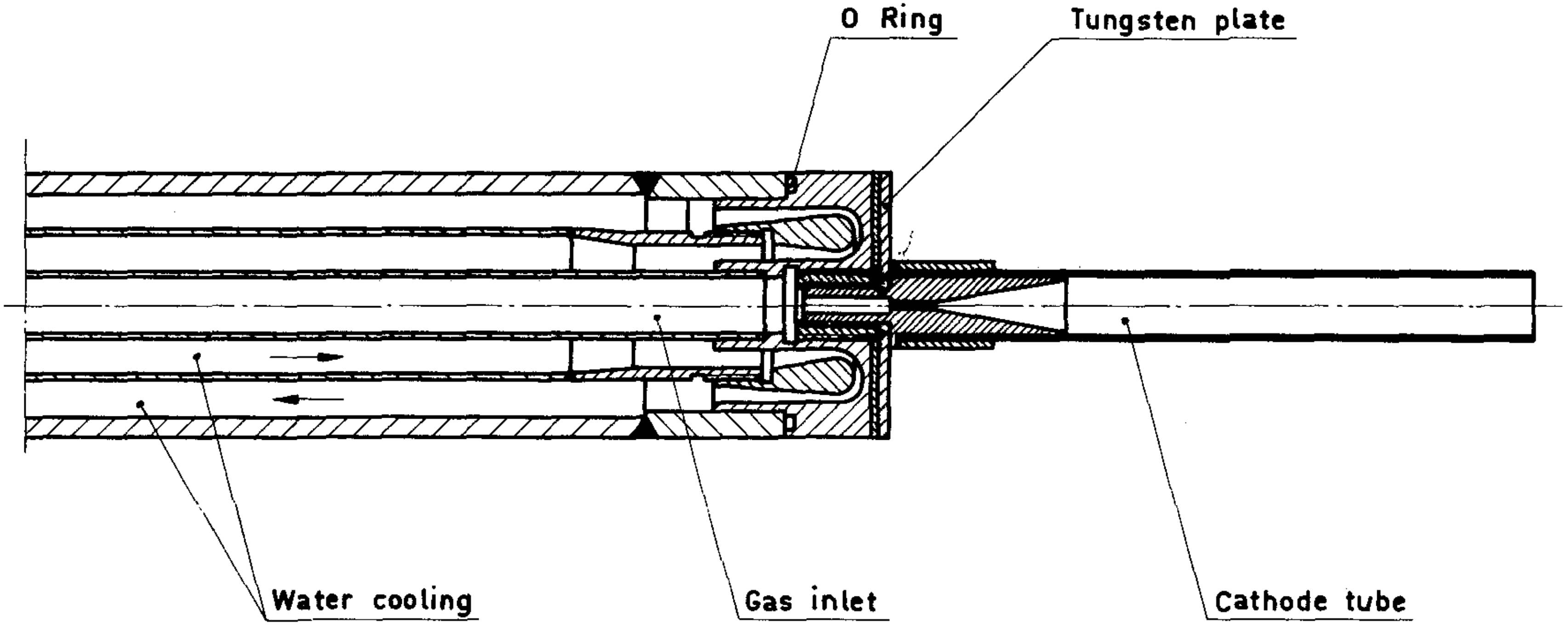


FIG.5 CATHODE ASSEMBLY

SCALE 1:2
EUR - 90 - 008

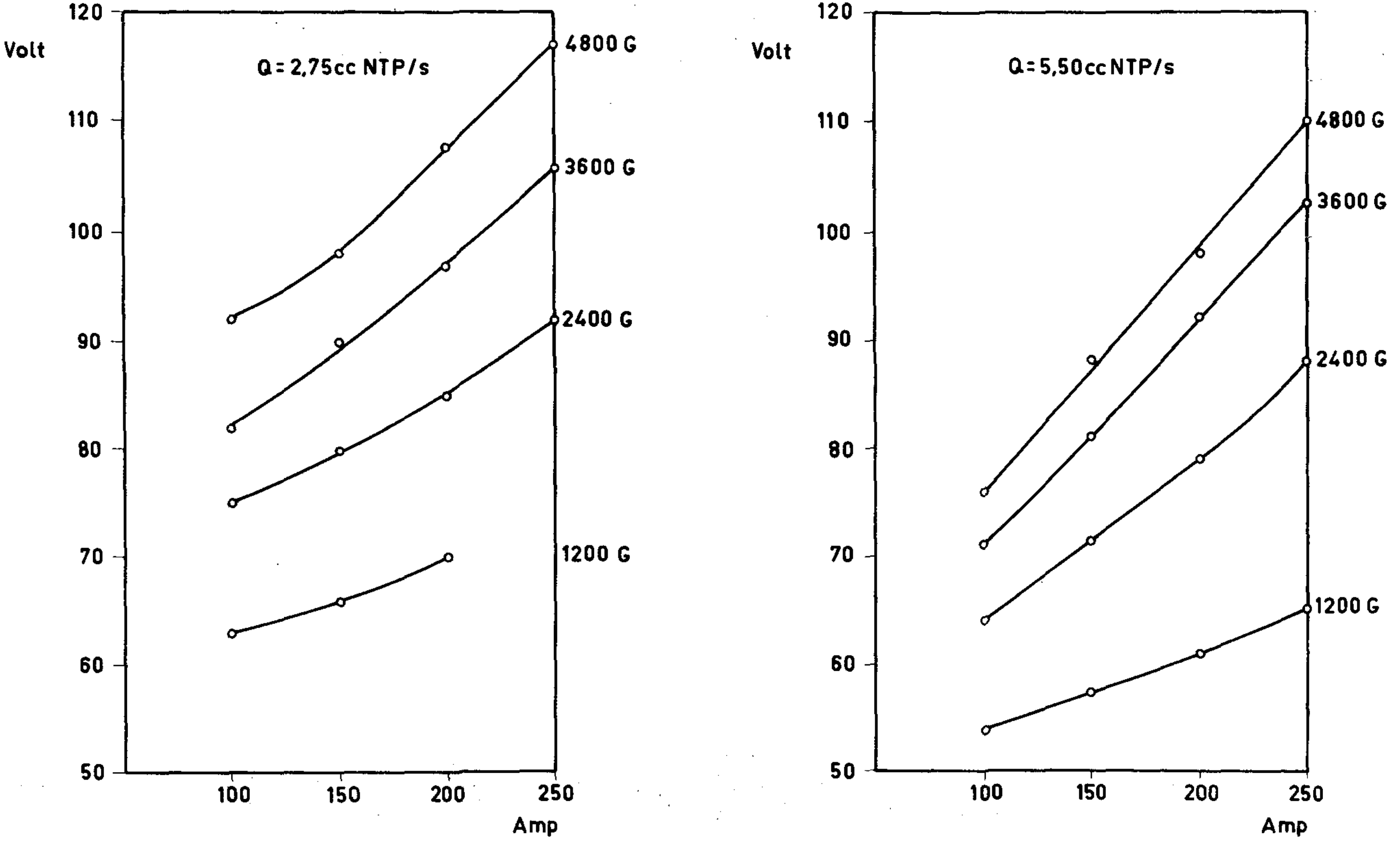


FIG. 6 CURRENT VOLTAGE CHARACTERISTICS

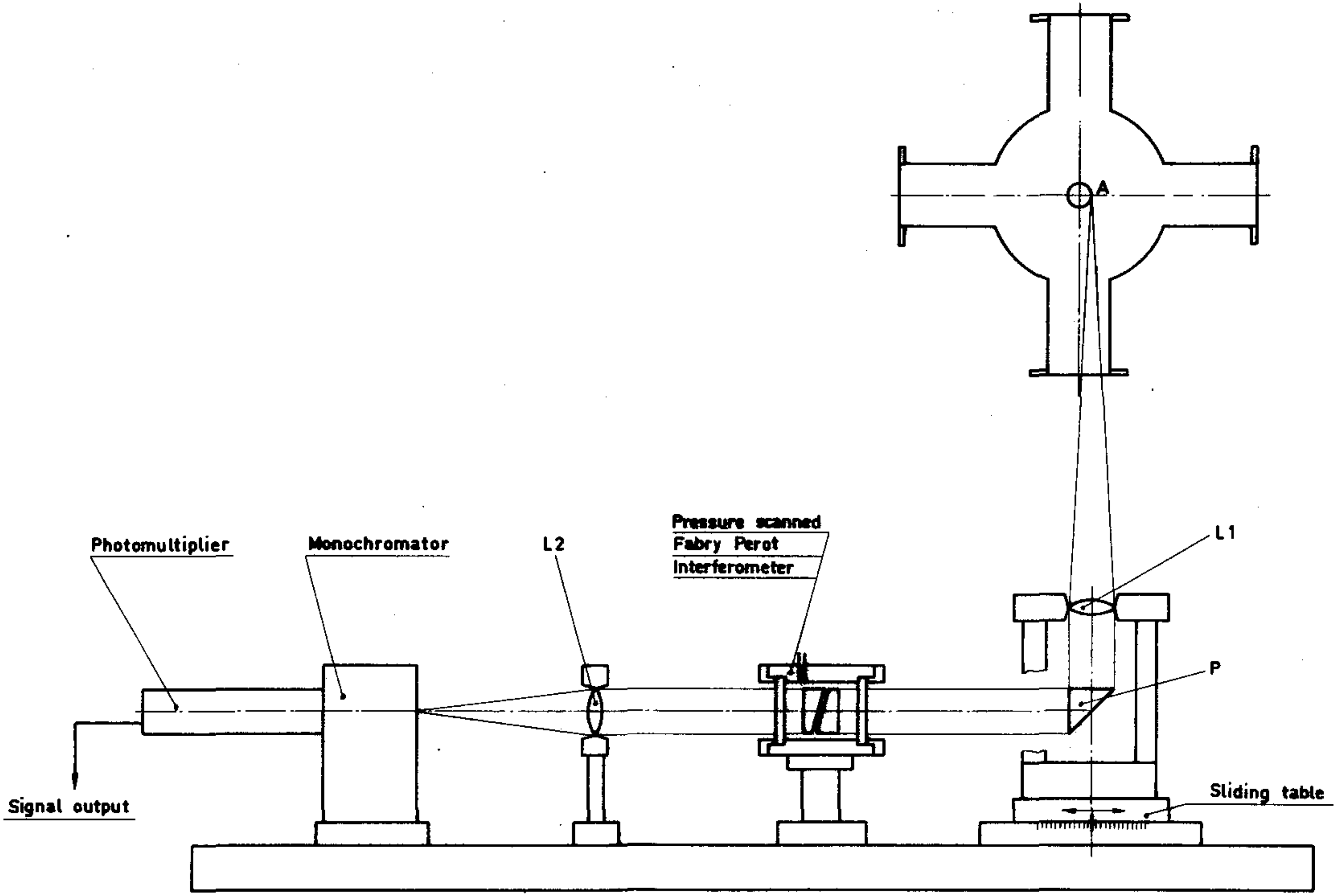


FIG.7 INFEROMETRIC LAYOUT

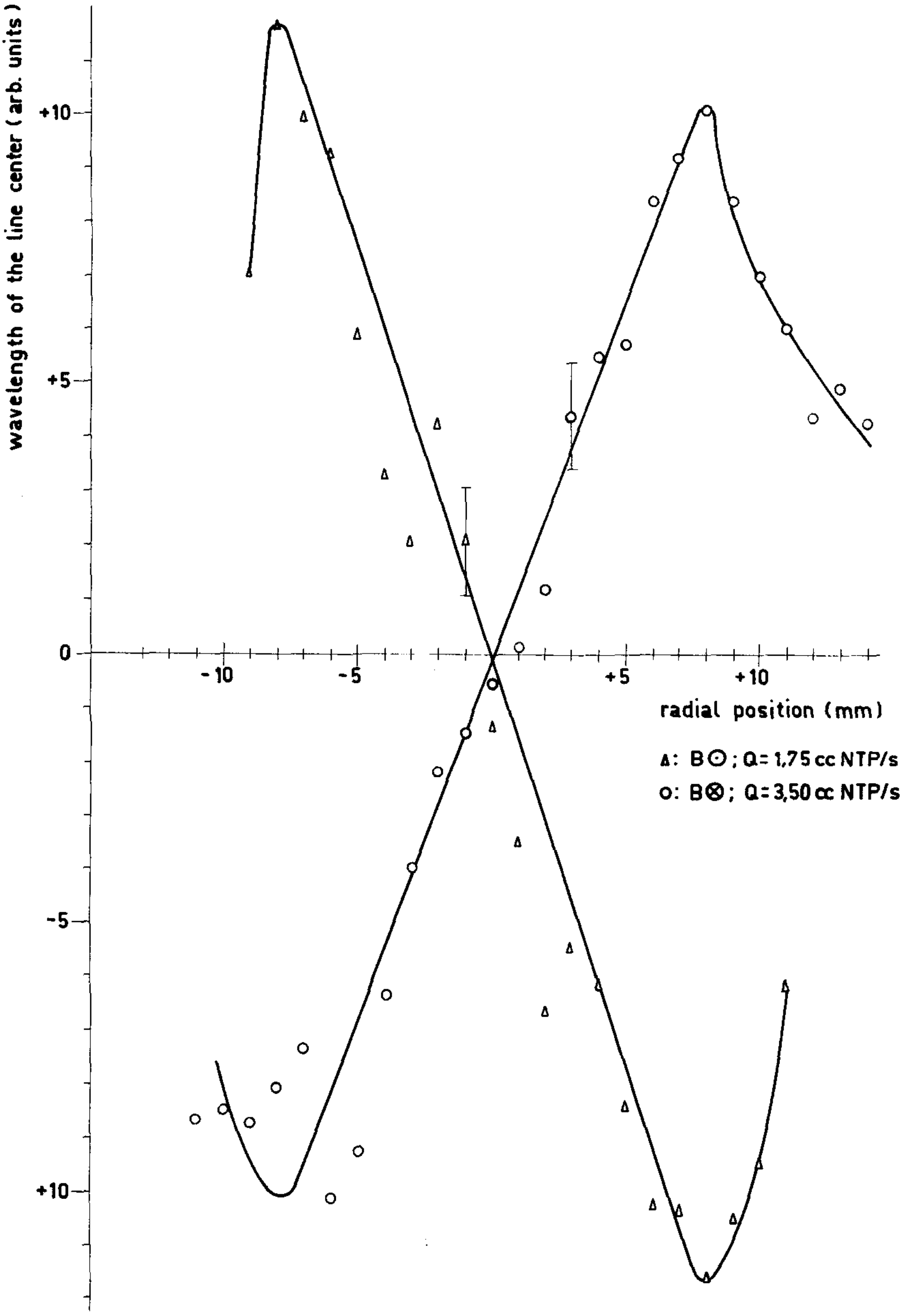


FIG.8 DOPPLER SHIFT IN THE ROTATING ARC

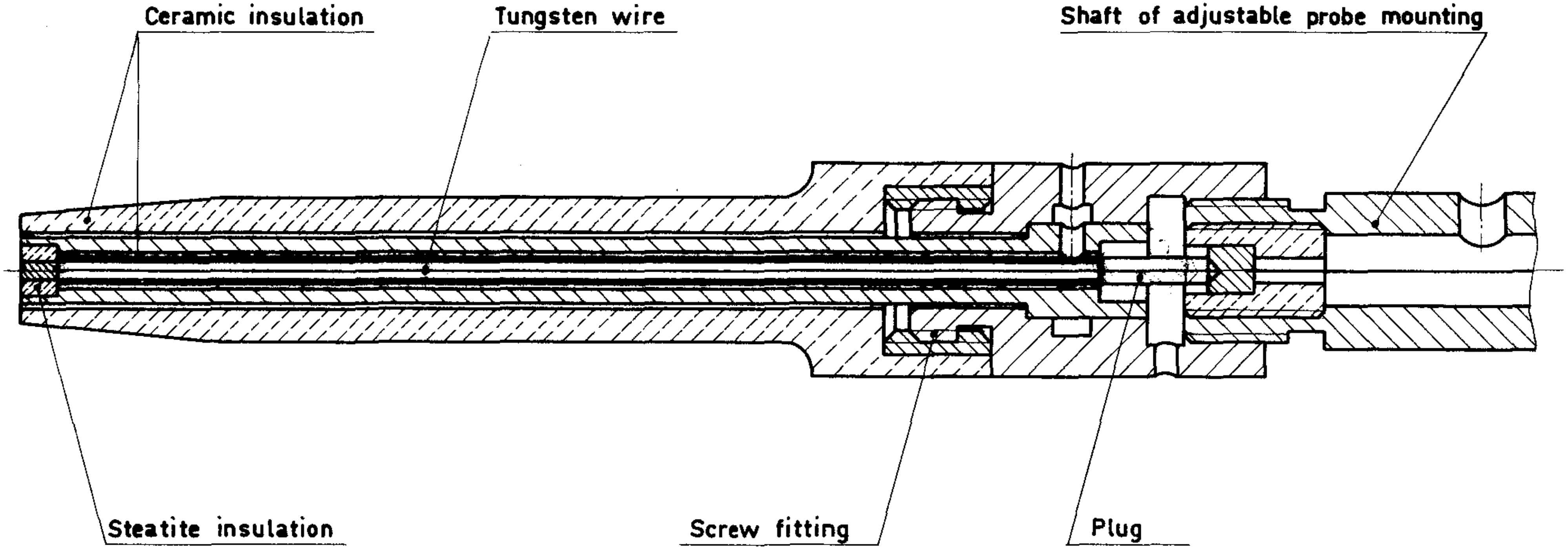


FIG. 9 LANGMUIR PROBE

SCALE 2 : 1
EUR - 90 - 010