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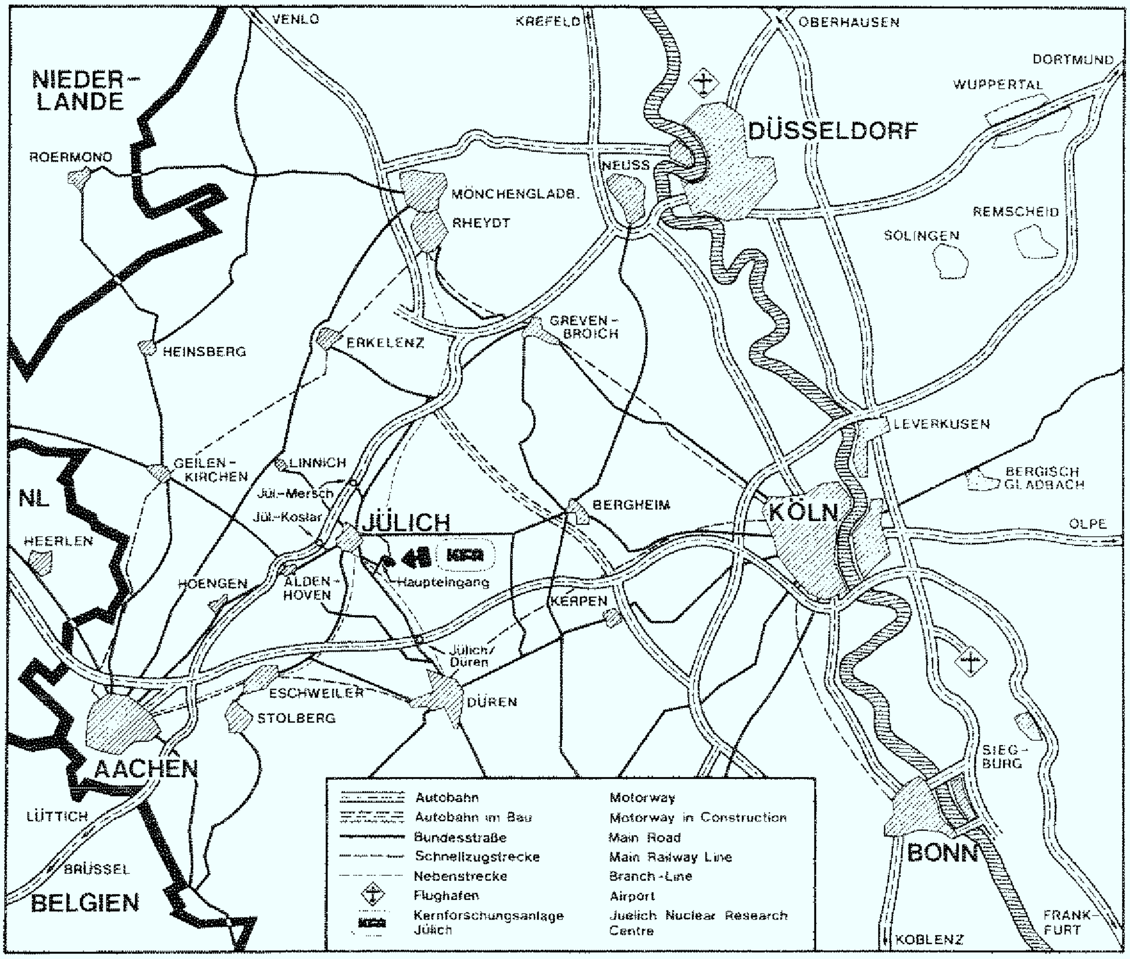

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THE BEHAVIOUR OF RG-CLEANING DISCHARGES IN LARGE VESSELS

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Abstract

The pressures at which RG-discharges can be ignited (P_I) and sustained (P_Q) have been measured in an unbaked SS vessel of 33 m^2 surface area and 11 m^3 volume. Different rf-electrode arrangements for the application in fusion devices have been tested. $P_Q = 5 \times 10^{-4}$ mbar can be achieved with an rf-anode in the center of the vessel. Higher pressures are necessary to sustain the discharge from anodes in portholes. Ignition is easily achieved by gaspuffing in the very vicinity of the rf antenna.

No bipolar arcs of considerable lifetime have been observed, whereas numerous unipolar arcs were triggered by surface contaminations. Their rate increases strongly with increasing current but decreases exponentially with time for fixed plasma conditions. A careful discharge conditioning by RG discharges in nonbakable devices or a prehandling at elevated wall temperature seem to be necessary. If they can be used, special means against unipolar arcs and their transition into a stable bipolar arc become unnecessary.

I. Introduction

Glow discharges in hydrogen are used to a rapidly growing extent as wall cleaning and conditioning procedure for fusion devices eg. /1, 2/. They will be implemented into large tokamaks like TEXTOR, JET, TFTR and JT60 /3/.

In previous studies /4, 5/ the conditions leading to a high cleaning effectivness of the glow discharge have been explored. These experiments have been performed in a SS simulation vessel of 3 m^2 inner area and a volume of $\approx$ 0.2 m^3. It has been found that, besides elevated wall temperature and large pump speed, a low pressure of hydrogen in the discharge is required for a high cleaning rate. This has led to the development of the RG (radiofrequency-glow)-discharge: a hollow cathode glow discharge wherein the anode is supported by a radiofrequency (rf)-discharge. The RG plasma in the simulation vessel can be sustained at a pressure of 10^{-3} mbar which is a factor of 10 lower than that at which conventional glow discharges quench. Another important parameter is the current density j. It was shown that an "optimum" value for j exists depending on the ratio Sp/A of the pump speed Sp and the wall area A of the device.

A scaling on the basis of these results leads e.g. to total currents for the RG discharges in TEXTOR and JET of 6 A and 40 A respectively (Sp/A is nearly the same in both cases as it was in the small scale simulation experiment).

There remain some open questions related to the operation of RG discharges in large vessels and at large total currents. A latent instability tends to switch the glow discharge over into an arc mode of operation /6/ when the total current is larger than 1 A. A concentration of the discharge power onto a very small area for a prolonged time could result in a serious damage of the wall surface. The process requires however a trigger mechanism /6/. For a given total current I, a glow discharge at low pressures tends to be more stable against arc formation than at higher pressure /6/. It can thus be expected /7/ that stable operation of a discharge at low pressures is alleviated in large devices. Other problems are associated with the initiation of the RG-discharge: The minimum pressure P_I at which ignition can be achieved in an RG discharge is lower that that of a pure glow discharge. Nevertheless P_I is still considerably higher than the quenching pressure P_Q near which the RG discharge would be operated. Flooding large vessels to P_I in order to achieve ignition and returning to P_Q could present a problem for the gas inlet and/or the pump system of a tokamak. Thus, appropriate ignition procedures have to be examined.

It is the aim of this work to explore the domains of P_I and P_Q for RG discharges in a large vessel and to find arrangements of electrodes applicable to large tokamaks. Attention is paid to the problems associated with the operation of RG discharges at total currents larger than 1 A. No emphasis was laid on the optimization of the cleaning properties of such a discharge in this vessel of which the walls remained close to ambient temperature. For those topics the reader is referred to /4, 5/.

II. Experimental arrangement

The vacuum vessel wherein the experiments have been performed is shown in figs. 1 and 2. It is the beam dump of the neutral beam injection test stand of the Jülich tokamak TEXTOR. The vessel has various large portholes (3 x NW 600, 8 x NW 250), an appendix of 1.2 m diameter and a structure on the top for the introduction of cryopumps. Stainless steel 1.4541 (AISI Type 321) is used as a wall material. The total inner area and the volume of the whole system are 33 m^2 and 11.6 m^3, respectively. The linear dimensions of the device are indicated in fig. 2. All flanges and connections are provided with rubber O-rings as vacuum seals. The pipes of the smaller portholes extend into the main volume by approximately 20 cm, (fig. 2, 16). Before any equipment was attached to the system, it had been thoroughly cleaned by a water jet. This eliminated residual material from a previous sand blasting procedure. The inner surface has been etched and rinsed with deionized water.

The vessel is pumped by a 3500 ls^{-1} turbopump via a NW 450 gate valve, adapted to one of the NW 600 portholes. The base pressure obtained was 2×10^{-7} mbar. A differentially pumped residual gas analyzer (Balzers QMG 112) was attached to one of the smaller ports. Vacuum gauges and a gas inlet system were mounted onto some of the small flanges. The system could not be baked out.

Several rf-electrode arrangements were mounted to the vessel (see fig. 2):

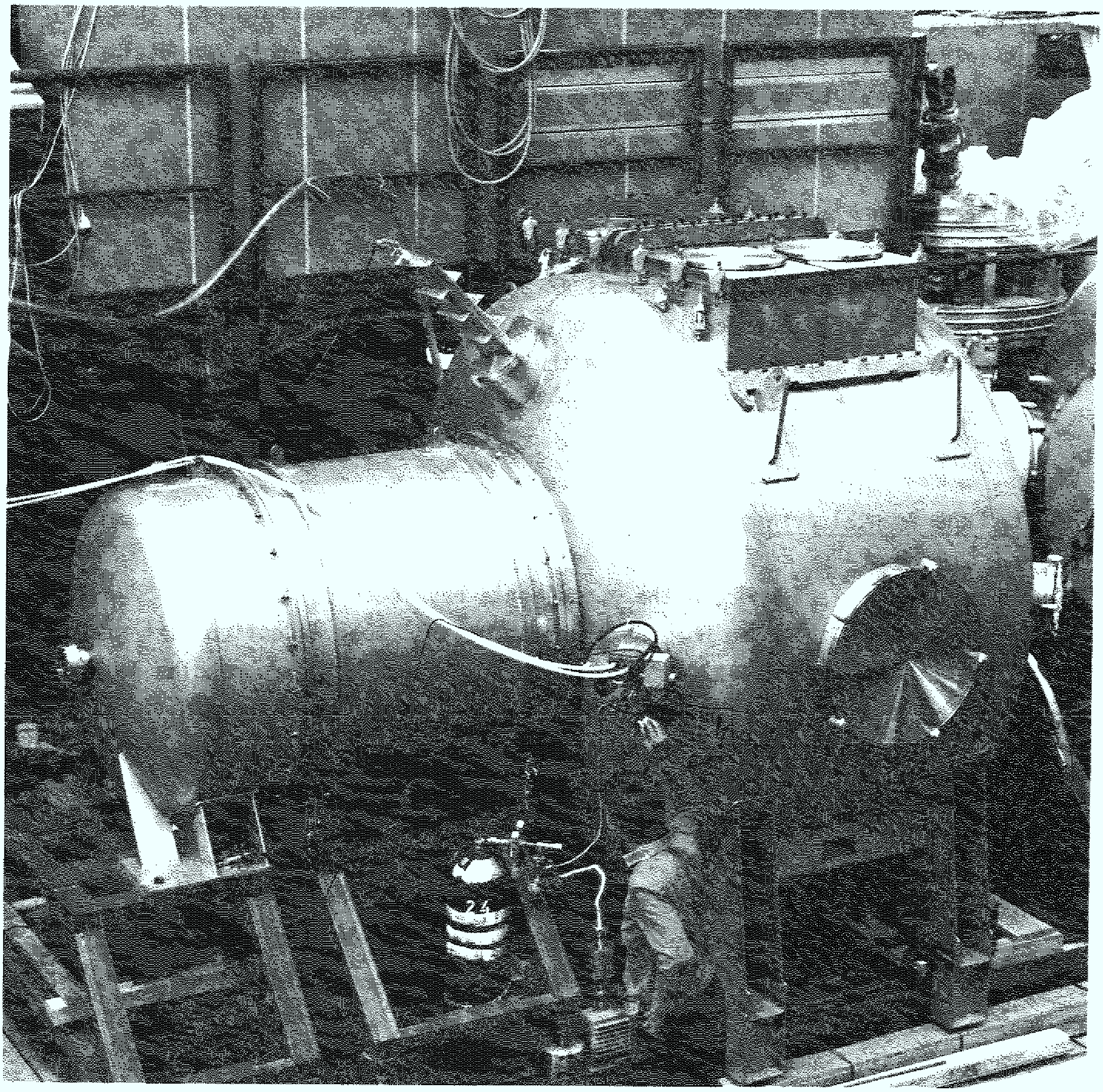

Fig. 1 Beam dump of the TEXTOR neutral injection test stand as used in this work

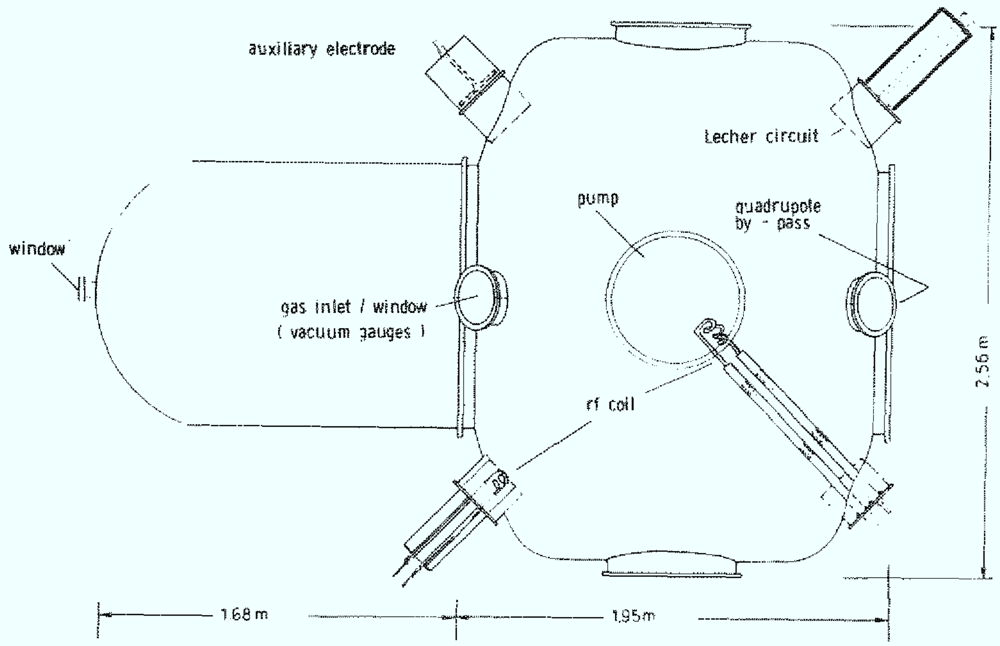

Fig. 2 Arrangement of antennas in the vessel, its dimensions are indicated.

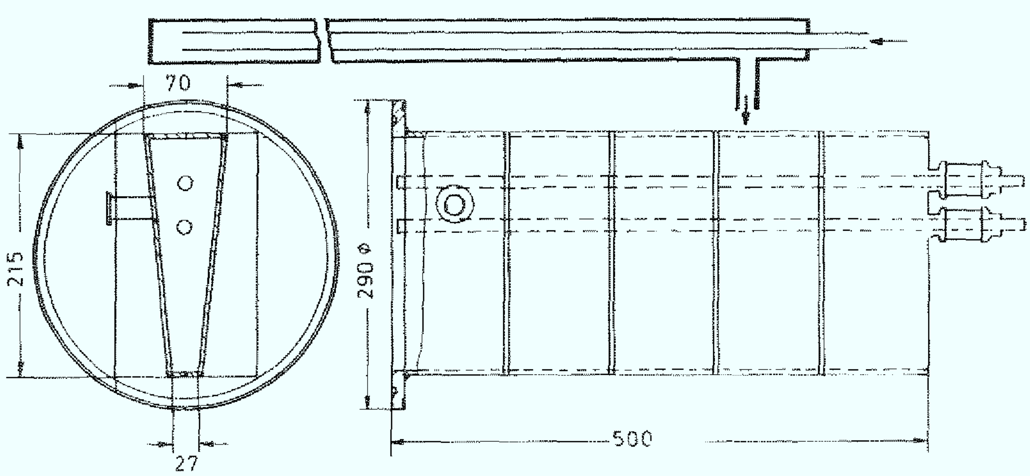

Fig. 3 Lecher line in a porthole having the geometry of the small JET ports. The cooling system is shown in detail above (all dimensins in mm).

- A pair of watercooled stainless steel-tubes, closed at one end, was introduced into a porthole having the triangular geometry of the small JET ports (for details see fig. 3). The tubes were isolated from the walls by $Al_2 O_3$ vacuum feedthroughs. They were arranged such that they acted as a "Lecher-circuit" when radiofrequency was coupled to them. A small pipe was installed near the open end of this circuit to allow gas puffing through an appropriate device. When attached to the main tank, the open end of the Lecher system was still separated from the free main volume by approximately 20 cm.

  The resonance frequency depends on the length of the system. It is ca. 100 MHz in the present case. The impedance of the arrangement at that frequency is $\approx 2\ \Omega$. Radiofrequency was applied to the system by a broad band power amplifier with a maximum output of 100 W, driven by a tunable 2 W master oscillator. The electrical coupling network is indicated in fig. 4, limiting the effective power to 40 W.

- Two different coil systems allowed the inductive coupling of rf-power into the main vessel. The first coil was inserted very near the center of the vessel; the second was fixed into a NW 100 porthole (see fig. 2). Both rf coils had 6 windings of 5 cm diameter and were 10 cm long. They consisted of a 6 mm hollow SS tube allowing water cooling. These tubes were guided coaxially from their vacuum feed throughs to the point were the curls of the coil started. In addition, both arrangements were provided with a third central tube for gas puffing close to the vicinity of the coil.

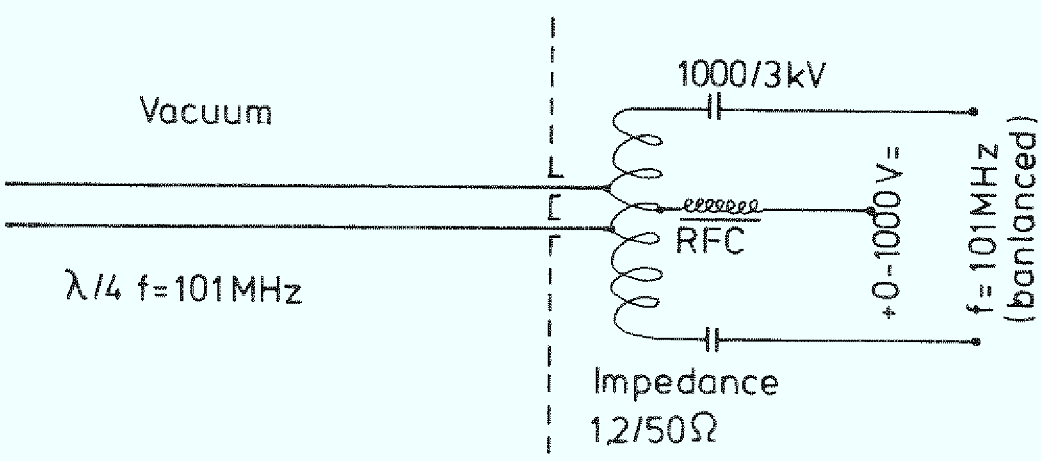

Fig. 4 Schematic diagram of the rf and DC coupling network for the Lecher liner

The radiofrequency was supplied by a 13,5 MHz rf generator with a maximum power of 70 W. The matching was achieved by the circuit indicated in fig. 5.

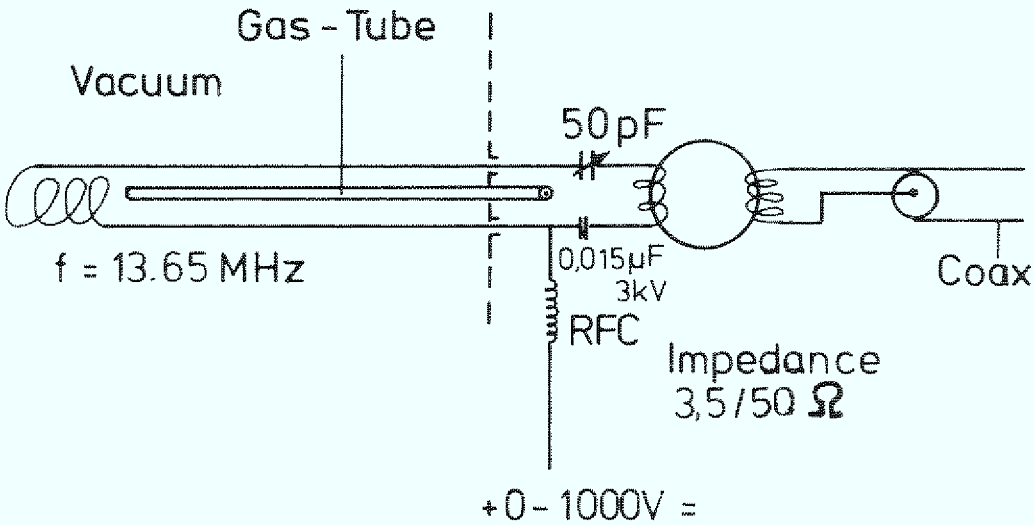

Fig. 5 Schematic diagram of the rf and DC coupling network for the coil anodes. The gas puffing tube is also indicated.

All three rf electrode systems could be coupled through an LC network (figs. 4 and 5) to a DC power supply (0 - 1 kV, 10 A max). This made the rf system either anode or cathode of the glow discharge. The load resistor used was 250 Ω in most cases.

An auxilary electrode was also mounted to the main tank. The system consisted of a port with triangular cross section (identical to the one shown in fig. 3). At the open end of the port, a triangular plate of 67 cm^2 area was placed, electrically insulated from the surrounding. When attached to the vacuum vessel the electrode was separated by 20 cm from the main volume by the pipe of the port.

The device used for gas puffing at the rf antennas consisted of a volume of 450 cm^3, filled with hydrogen at various pressures. The gas was suddenly expanded into the main tank by means of an electromagnetic valve and was guided by a tube to the vicinity of the antenna. All measurements were performed in hydrogen as a working gas.

A TV camera and a monitor were used to control the state of the discharge during the experiment.

III. Results and Discussion

III. 1. Pressures for ignition and quenching of RG-discharges

To measure the pressures P_I at which discharges could be ignited and P_Q at which they quenched, a constant throughflow of hydrogen through the vessel was first established. The gate valve was then closed, leading to a continuously rising pressure. After ignition the gate valve was reopened and the flow eventually reduced until quenching occured. Ignition and quenching were observed either by light emission or by recording the discharge current. +)

III.1.1 Pure rf-discharges

The variation of P_I and P_Q for pure rf-discharges with the rf-power are shown in fig. 6.

In all three cases tested here, it is observed as a general trend that both P_I and P_Q decrease as a function of the rf-power, tending to saturate at power levels larger than 20 W. Except for the case of the central coil the influence of the rf power on P_Q is less pronounced than that on P_I. From fig. 6 it is obvious, that a large geometry dependent effect exists. The ranges of P_I and P_Q seem to be rather unaffected by the type of rf coupling (inductive or Lecher circuit). Both types of antennas, when located in a (small) port, i.e. somewhat separated from the main volume, require a P_I which is a factor of three to five higher than that for the central coil. For P_Q the situation is similar; it is lower by about a factor of 5 in the latter case. The central coil seems to be the most favourable location for the antenna - $P_I = 1.3 \times 10^{-2}$ mbar and $P_Q = 5.5 \times 10^{-4}$ mbar can be achieved with a power of 70 W.

+) In some cases (RG-anode in the center of the vessel) the pressure could be reduced to very low values with the discharge still maintained, but in a mode (Townsend regime) characterized by high voltages and extremely low currents. Since the cleaning effectiveness increases with the current density /5/ it is desirable to operate the discharge in the "regular" glow domain with high current. The transition pressure to the low current mode was regarded as the quenching pressure P_Q in these cases.

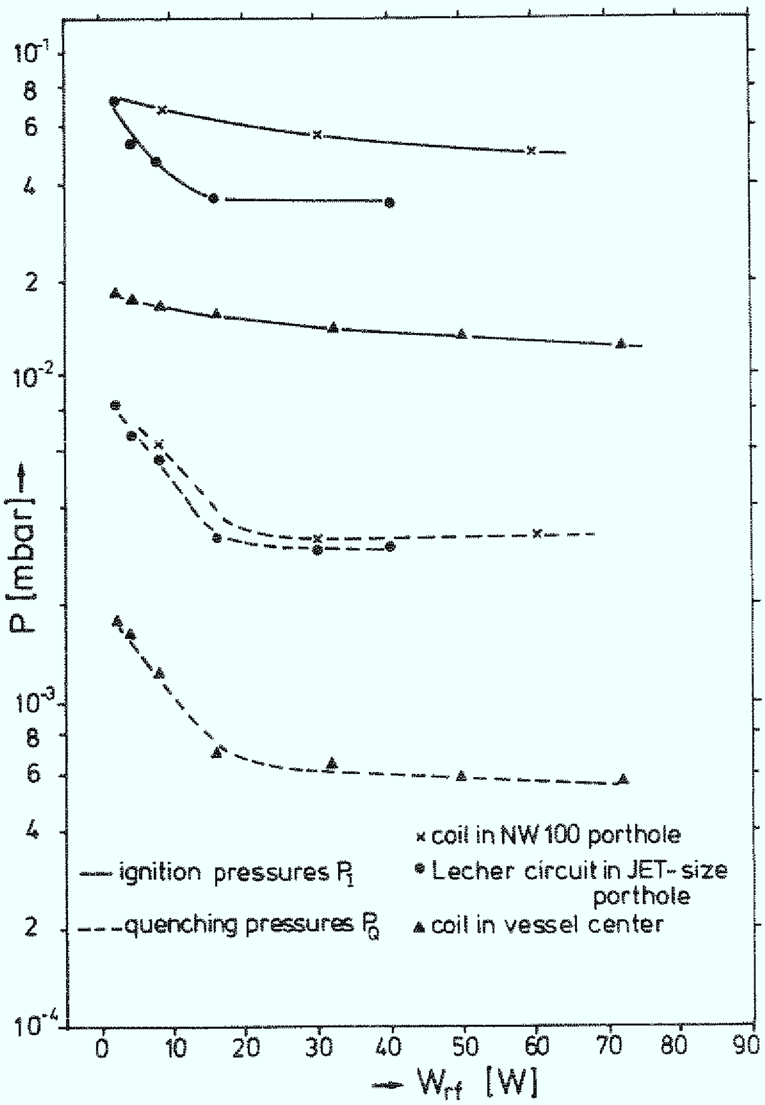

Fig. 6 Variation of ignition (P_I)- and quenching (P_Q) pressures of pure rf discharges as a function of the rf power W_{rf}.

A problem arose with the tuning of the rf-circuits. When the systems are tuned for minimum reflected power before ignition, a certain amount of reflected rf is measured in the presence of the plasma. This is particularly pronounced in the case of the Lecher circuit. The effect can be expected because of the electrical conductance and dielectric constant of the plasma. The mistuning decreases as the pressure is decreased. It can in principle be compensated by electronic means (feed back control) but it was regarded to be of minor importance here due to the saturation behaviour observed for P_I and P_Q at powers larger than 20 W. Care has to be taken, however, if transitorized rf generators are used, since the reflected power might damage the booster. All rf-power values given in this work are those prior to ignition.

III. 1.2. RG- and pure glow-discharges

How a DC-voltage U affects P_I and P_Q is shown in figs. 7 - 9 for several rf power levels. The rf circuit always acted as anode and the main vessel as cathode; the values given for U are those prior to ignition.

When the rf antennas are situated in portholes (figs. 7a and 8a), the P_I vs. U curves display pronounced minima when U ≈ 100 V. Their values are 5 x 10^{-3} mbar for the Lecher circuit (40 W_{rf}) and 16 x 10^{-3} mbar for the coil in the NW 100 porthole (60 W_{rf}). When the voltage is raised, P_I increases to values which are even higher than those observed without DC voltage; it goes through a maximum and decreases again. This behaviour is similar to that observed earlier in the smaller simulation apparatus /5/. Both minima and maxima of the P_I curves are shifted towards higher voltages when the rf power level is increased. In the case of the Lecher circuit it was observed by light emission that, at high pressures, the plasma is driven into the porthole with increasing voltage. It can be suspected that at the anode the gain of electrons from the main volume competes with the loss of charge carriers to the neighbouring walls of the portholes. At high DC voltages the system tends to approach the pure glow discharge. P_Q is observed to decrease as a function of U in both cases (figs. 7b and 8b), showing less pronounced relative minima and maxima. The curves tend to saturate at U ≳ 500 V and reach a final value of P_Q around 2 - 3 x 10^{-3} mbar.

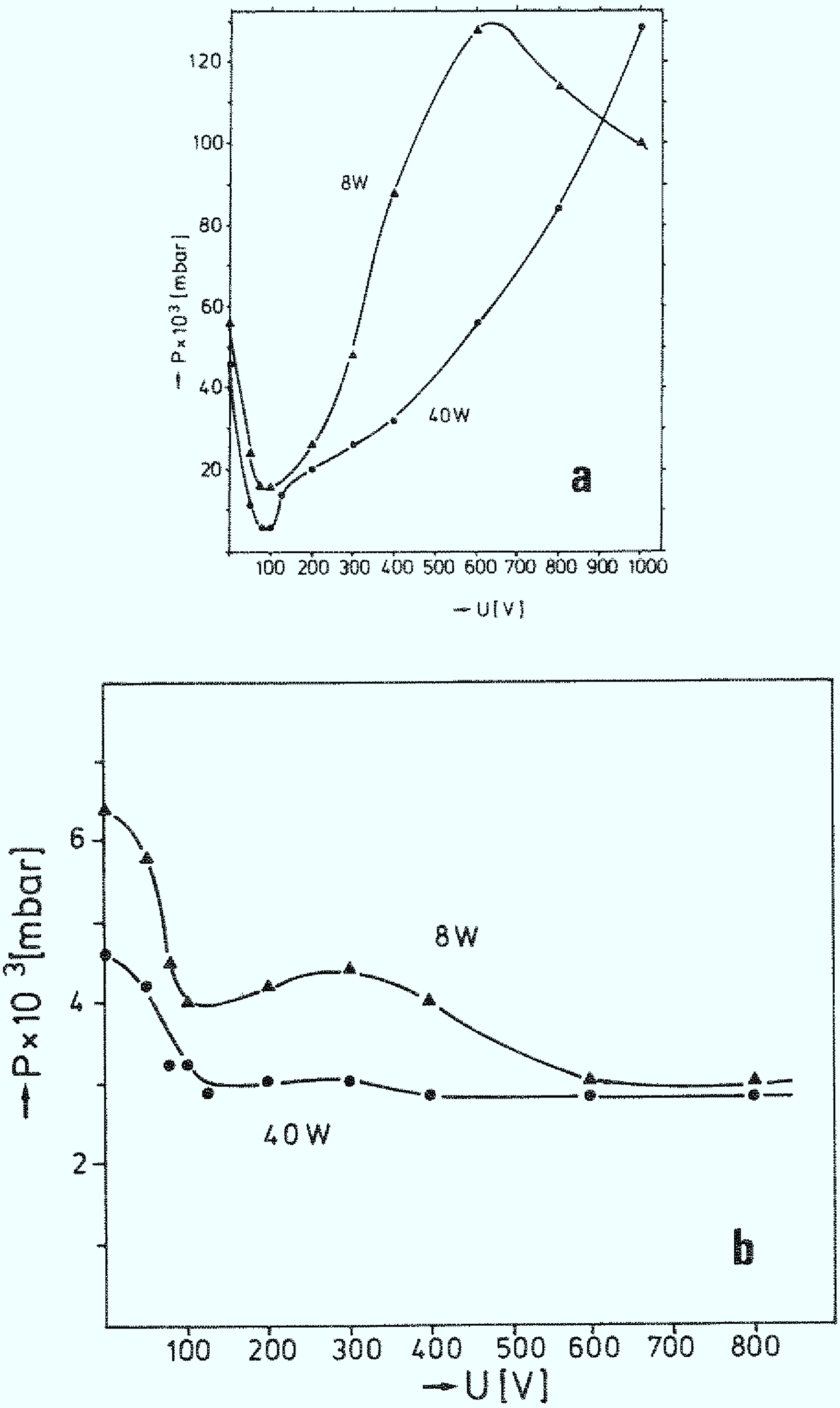

Fig. 7 Variation of the ignition (a)- and the quenching (b) pressures for RG discharges with the Lecher antenna as a function of the initially applied voltage U at two rf power levels.

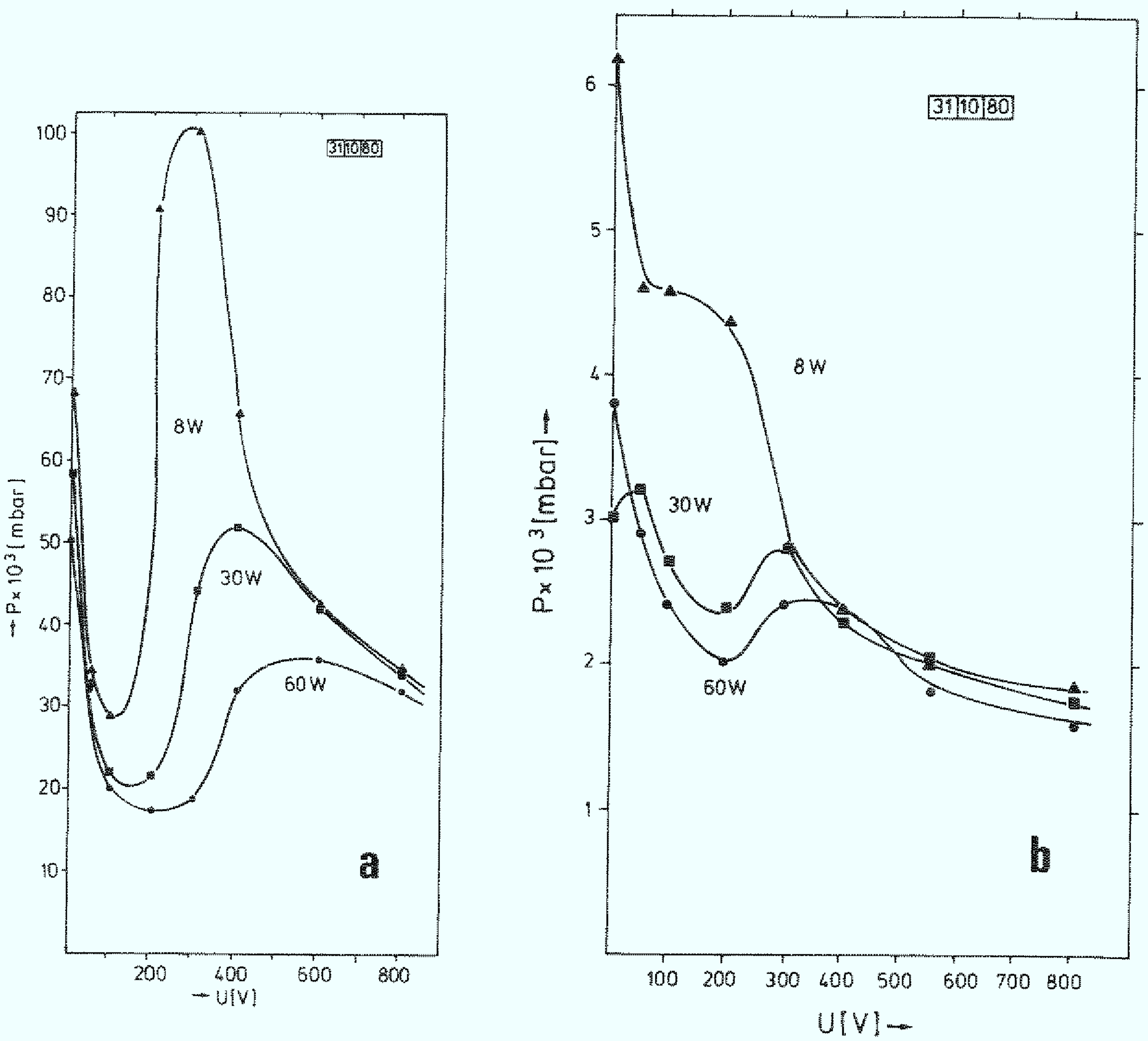

Fig. 8 Variation of the ignition (a)- and the quenching (b) pressures for RG discharges with a coil antenna in a NW 100 porthole as a function of the initially applied voltage U at three different power levels.

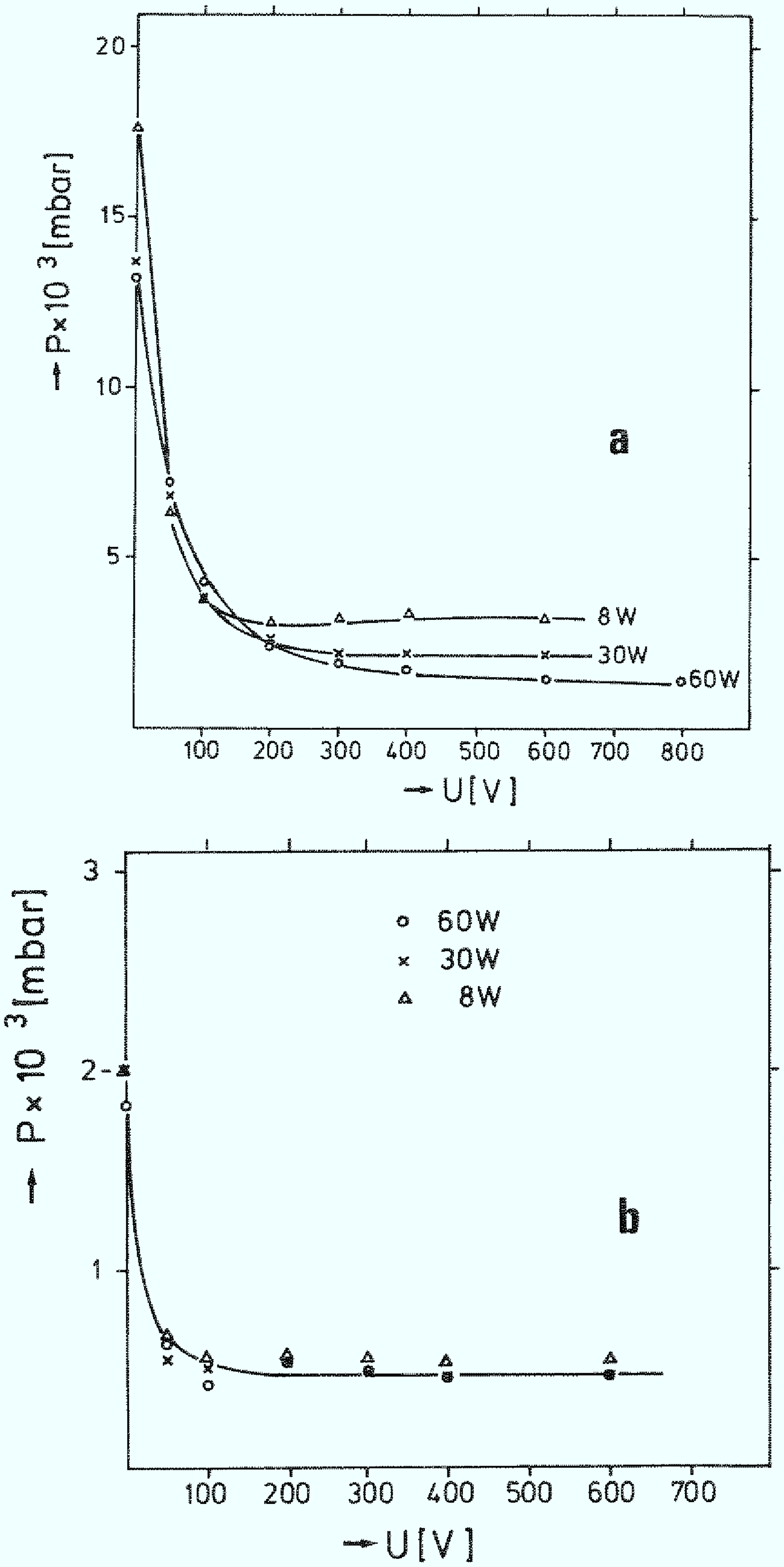

Fig. 9 Variation of the ignition (a)- and the quenching (b) pressure for RG discharges with a coil antenna in the center of the vessel as a function of the initially applied voltage U (three rf power levels). It is apparent that the quenching pressure is almost independent on W_{rf}.

When the plasma anode is situated in the center of the vessel (fig. 9a, b), an increase of the DC-voltage decreases smoothly both P_I and P_Q. Saturation is approached for $U \geq 300$ V. Beyond 8 W, the influence of the rf power level on P_I is small, and not significant in the case of P_Q. The limiting pressures obtained are 1.5×10^{-3} mbar for P_I and 0.5×10^{-3} mbar for P_Q.

To facilitate the comparison of the results obtained with different arrangements , the relevant P_I and P_Q curves are compiled in fig. 10, together with the values obtained for pure glow discharges from the respective anodes. The following conclusions can be drawn:

- The ignition and quenching pressures of pure glow discharge are always higher than those of RG discharges with rf supported anodes,
- when the RG-anode is located in a porthole of reduced aperture, it is not very important whether the rf power is coupled into the system via a Lecher circuit of a coil. There exists then an optimum DC voltage to alleviate ignition,
- the by far lowest P_I and P_Q values are obtained, when the RG-anode is situated in the middle of the vessel, i.e. when the system most closely resembles a central anode and a concentric hollow cathode.

The low P_Q pressure at which the RG-discharge can be operated using a central anode is very favourable with respect to an effective cleaning. It can be expected, that the cleaning rate under otherwise comparable conditions should be even larger in this case than in the previous simulation study /4,5/.

III.1.3. Gaspuffing

It is easy to ignite RG-discharges with each of the antennas by means of localized gas puffing: A constant throughflow of hydrogen was established at the low pressure required for cleaning purposes. The rf power and glow discharge voltage were switched on and a gas-puff-volume (450 cm^3) filled with hydrogen was suddenly expanded into the vessel.

Ignition occurs when the particle density at the coil or the open end of the Lecher circuit rises for a short time to an adequately high value. This was achieved here by guiding the pressure wave in a tube of appreciable con-

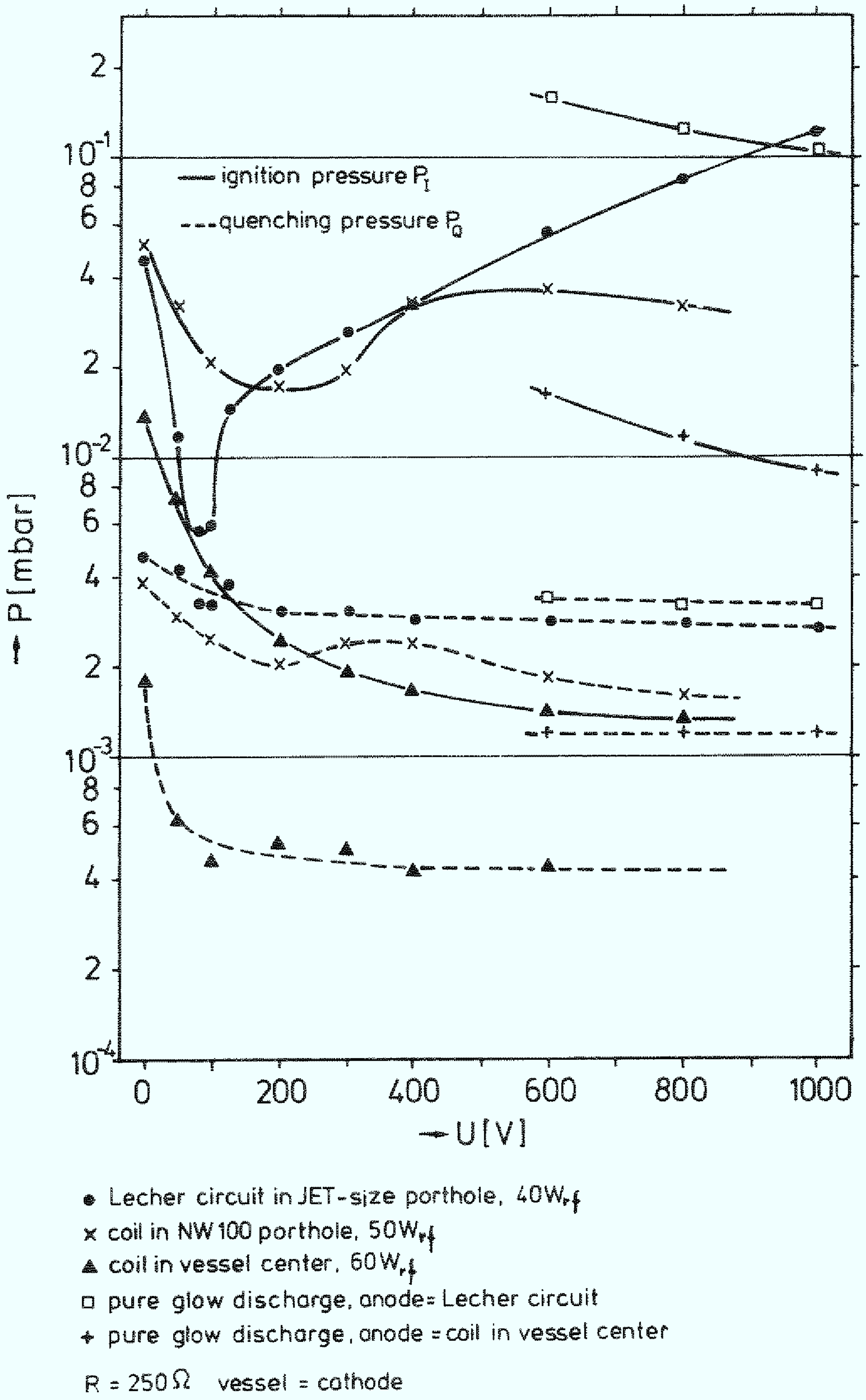

Fig. 10 Ignition (full line) and quenching (dashed line) pressures for RG discharges and for pure glow discharges with various anode arrangements, as a function of the initially applied voltage.

ductance to the very vicinity of the antenna before it is allowed to expand into the main volume. Consequently, a high starting pressure for the wave is more important than the total amount of gas (mbar x liters) introduced into the tank. Under these conditions the RG discharge could be initiated without flooding the vessel to a large extent.

In the case of the Lecher line and of the coil in the NW 100 porthole, a starting pressure of 5 mbar in the gas-puff-volume sufficed to ignite the plasma (W_{rf} = 40 W, U = 90 V); this gave rise to a pressure spike in the main volume of 6 - 8 x 10^{-4} mbar above the constant level. In the case of the central coil the starting pressure had to be increased to 10 mbar (W_{rf} = 30 W, U = 100 V) due to the larger volume and smaller conductance of the guiding pipe. Here, the pressure spike was 10^{-3} mbar.

Gas puffing offers a simple and reliable way to ignite RG-discharges. In the case of machines working with tritium, this solution may however be impeded by safety considerations, which might make a simple technical solution impracticable.

III.2 Current-Voltage-characteristics

The current (I)-voltage (U)-characteristics have been measured for a number of RG-discharges. When not stated otherwise, the wall of the vessel was grounded and one of the antennas acted as an anode. The load resistor was 250 Ω, limiting the accessible current to $\approx$ 3.2 A. In a few cases the discharge was operated at currents up to $\approx$ 8 A with a resistor of 50 Ω. The voltage U was measured across anode and cathode directly, representing the floating potential to within 20 - 30 V /5/.

The I-U-curves for GD discharges with different rf circuits are shown in figs. 11 - 13. In all cases the voltage needed to establish a given current I increases at first rapidly when I is raised. It saturates for currents larger than $\approx$ 1 A. In some cases it was difficult to obtain reproducible I-values for increasing and decreasing U ("unstable" regime). In these domains either new parts of the vessel (portholes) were covered by the plasma or the discharge type in the portholes changed from normal to a hollow cathode glow. The discharge is still quiescent. It is not an arcing effect.

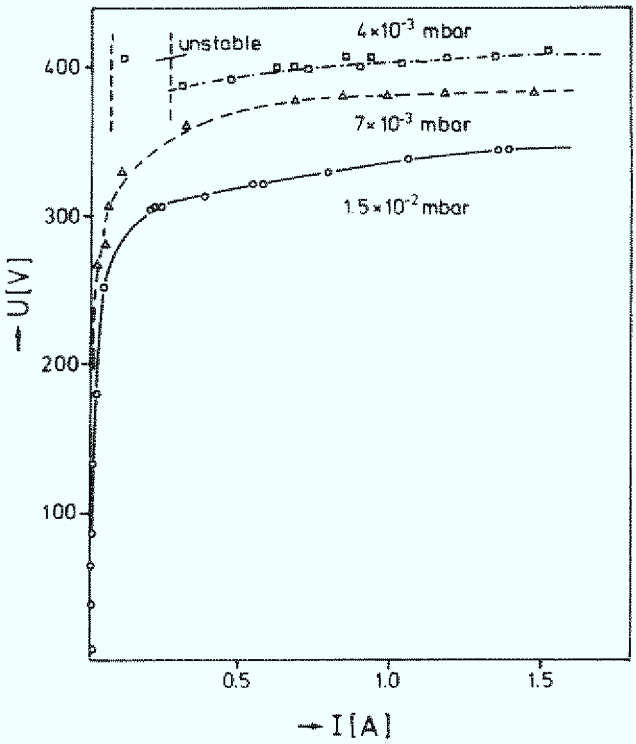

Fig. 11 Voltage (U)- current (I) characteristics of RG discharges with the Lecher antenna at various pressures. With the exception of the steep increase at low current, the curves are almost independent on the rf power.

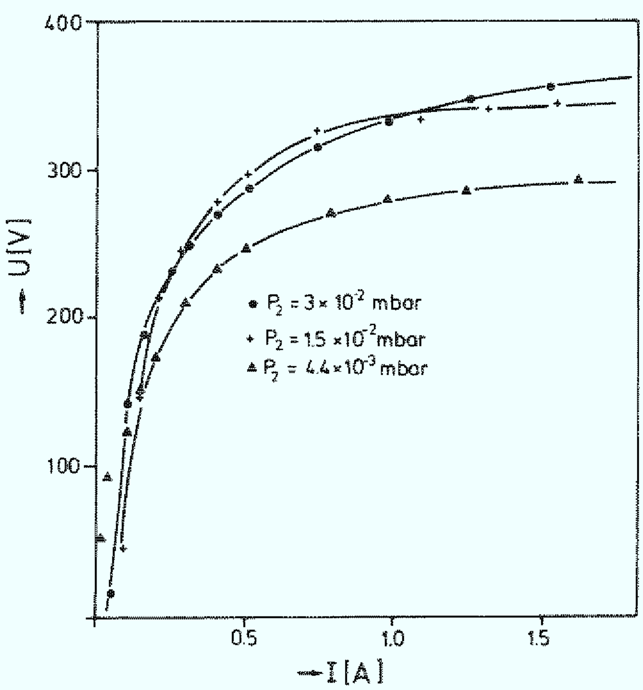

Fig. 12 Voltage (U)- current (I) characteristics of RG discharges with a coil antenna in a NW 100 porthole at different pressures. With the exception of the steep increase at low current, the curves are almost independent on the rf power.

Figs. 11 - 13 show the I-U characteristics up to 1.5 A. A smooth continuation of the curves was observed up to 6 - 8 A (see however §III.3). The characteristics depend weekly on the rf-power in their steeply ascending part: the application of a higher rf power decreases U at a given current. At I $\approx$ 0.3 A all curves are essentially independent on W_{rf}.

Higher voltages are required, to establish a given current when the Lecher circuit is the anode (fig. 11). The saturation voltage increases when the pressure is decreased, whereas in the other cases a decrease was observed. We believe that the difference results mainly from the fact that the Lecher circuit is still separated from the main volume by a 20 cm long porthole at ground potential. For $P_2 = 4 \times 10^{-3}$ mbar the saturation voltage is 400 V for the Lecher anode and $\approx$ 300 V when different coils are used. In the latter two geometries the I-U discharge characteristics are almost identical (cf. fig. 12, 13).

In order to check the homogeneity of the discharges and in particular their penetration into the portholes, the current I_{probe} flowing to the auxiliary electrode has been measured (cf. fig. 14). It is plotted (fig. 15a,b) as a function of the total discharge current I_{tot} for the two coil antennas at different hydrogen pressures.

Both arrangements behave similarly. At small total currents and at low pressures I_{probe} increases rapidly when I_{tot} is raised. It increases thereafter linearly when $I_{tot} \gtrsim 0.3$ A. In this domain the auxiliary electrode is reached by a certain fraction of the total current; the current density is about 1/10 of the averaged current density to the wall of the main vessel+). Obviously some discharge current penetrates into the portholes even at low pressure. The ratio I_{probe}/I_{tot} does not change significantly when the pressure is varied and does not depend on the location of the anode.

For both anodes the curves at $P \approx 1.5 \times 10^{-2}$ mbar display a flat part at $I_{tot} \approx 1$ A. This is probably due to the fact that new parts of the surface are covered by the discharge (see above).

+) Effects due to the potential difference of $\approx$ 200 mV which is induced by the internal resistance of the amperemeter between electrode and vessel wall have not been considered.

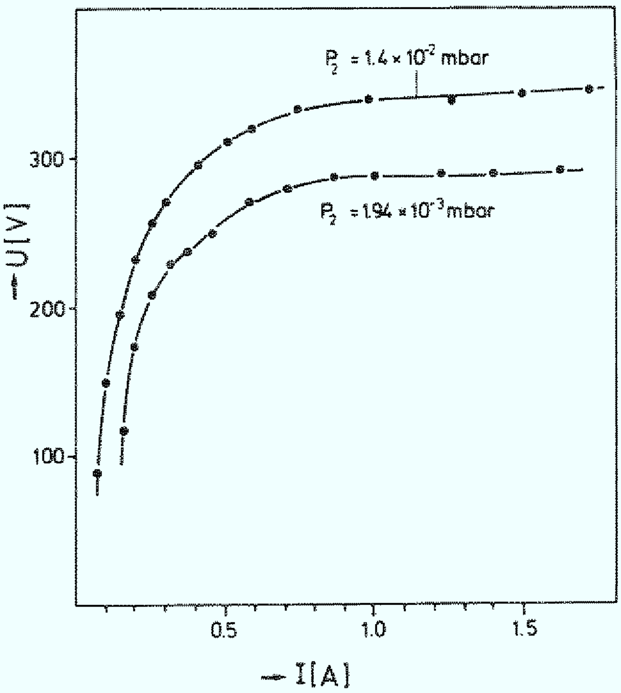

Fig. 13 Voltage (U) - current (I) characteristics of RG discharges with a coil antenna in the center of the vessel at two different pressures. With the exception of the steep increase at low current, the curves are almost independent on the rf power.

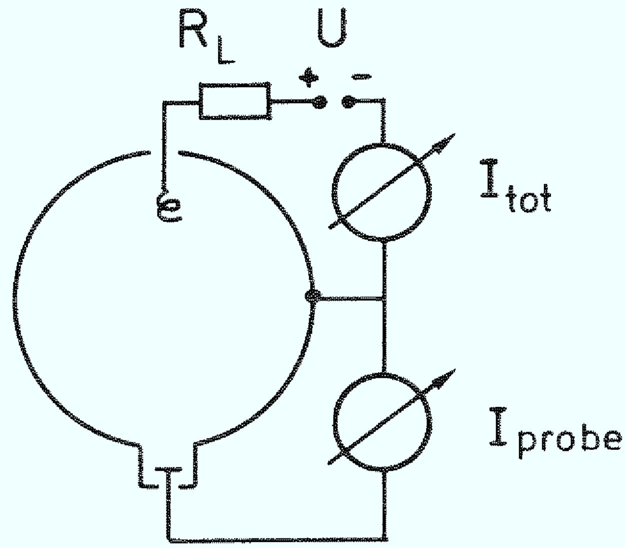

Fig. 14 Electric circuit diagram of the arrangement used for measurements of the current to the auxiliary electrode.

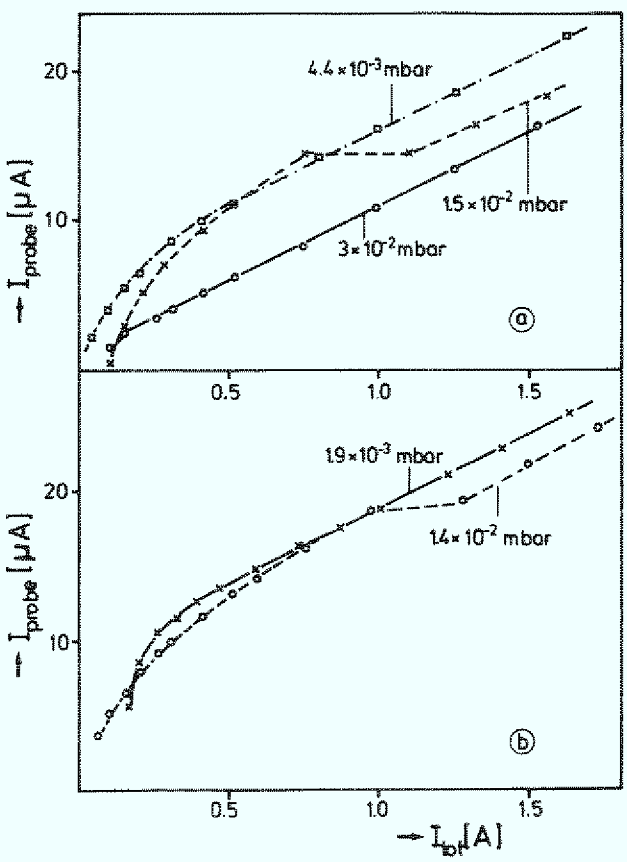

Fig. 15 Current to the auxiliary electrode (I_{probe}) versus total current of the discharge (I_{tot}) for

a) coil anode in a NW 100 porthole

b) coil anode in the center of the vessel

In large toroidal devices, it may be useful to distribute the current among several anodes.[+)] This alleviates the cooling problems, allows to operate at low pressures and ensures a better homogeneity of the discharge. This is easily achieved provided each anode has a separate load resistor R_j. The current through each anode is then proportional to $1/R_j$. With one common load resistor, the power might concentrate on a single anode. This could in particular occur at low pressures where the different anode plasmas have been observed to quench in the order of their respective P_Q.

A test has been made to check whether a discharge between an (r_f)-anode and cold, auxiliary cathodes situated in protholes and insulated from the vessel might be suited for cleaning purposes. The glow current which could be drawn under those conditions, was smaller by orders of magnitudes than when the whole vessel acted as a hollow cathode. Since the cleaning rate is proportional to the current density on the wall /5/, this arrangement is unfavourable. Larger currents could in principle be achieved using hot cathodes as electron emitters. These are undesirable in tokamak systems since evaporation effects could occur.

III.3. Arcing

III.3.1. General remarks

Arcing in tokamaks may lead to the evaporation of metallic atoms and thus represent as important source for the impurities observed in the plasma. The present state of knowledge on arcing phenomena in fusion devices has been recently surveyed in a workshop /8/ and has been extensively reviewed /9, 10/. A close similarity between the arc spots in a tokamak and unipolar arcing phenomena occuring in other types of plasma discharges seems to exist.

It is generally accepted, that the arc is driven by the potential difference between plasma and wall ("unipolar" arc). The nature of the trigger mechanism is however still unclear. There is considerable evidence that, besides inherent material parameters /11/, the presence of surface contaminants such as residual grease, oil or other locally insulating substances on the metallic wall can lead to the initiation of arcs /9/.

+) B. Brandt, British Patent 1222917

This statement is supported by the observations made in our laboratory /5/ that the arcing frequency is high in unbaked devices, but that it falls down to zero when the UHV components have been baked in situ under vacuum at a temperature of 200 °C or more. This underlines the importance of foreseeing baking procedures for the vacuum vessels of fusion devices. It suggests furthermore that operation with walls at elevated temperatures should drastically diminish the arcing problem.

Many experiments on unipolar arcing reveal a conditioning effect. The arcing rate decreases as a function of time /1,5,6,8/. From detailed studies of negatively biased samples in a rf-plasma /11/ it has been shown that the arcing rate decreases exponentially with time for fixed sample and plasma conditions. This suggests the presence at a finite number of initial arcing sites which are gradually "burnt out".

III.3.2. Observation of arcs in the RG-discharge

The measurements presented in this paper were performed in a system which could not be heated. Thus arcing occured during the RG discharges.

No arc phenomena could be identified during pure rf discharges; they appeared only when an additional voltage was applied. The arcs were detected by their light emission and measured through the resulting current spikes which are superimposed on the otherwise constant RG current. The observations reported here, refer to experiments made in the pressure domain between 10^{-1} and 10^{-4} mbar.

Two types of arcs occured:

- In the very initial phase of RG-discharge operation using the Lecher antenna columnar arcs (resembling plasma jets) struck between the anode and the nearby wall of the porthole. Individual arcs might burn during several seconds. Their frequency gradually decreased and the phenomenon disappeared completely after several minutes of operation. This disappearance was probably accelerated by the gradual elevation of the porthole temperature during operation (see above): After about one hour of RG-discharges a temperature of 80 °C was measured at the flange. No similar effects were observed near the other anodes.

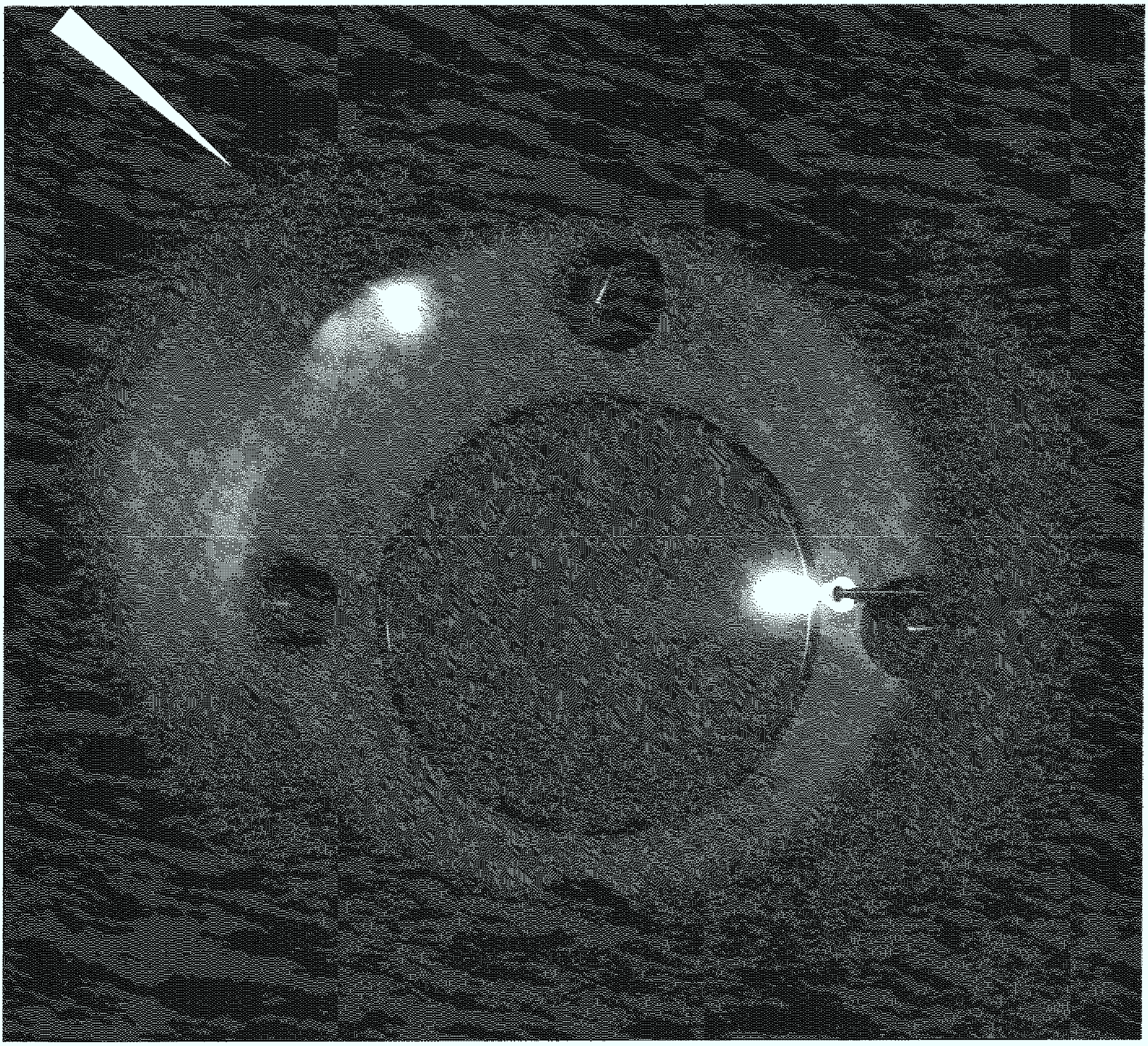

Fig. 16 Unipolar are striking across the cathode sheath. It is located at the upper left corner of the picture (arrow). The bright structure on the right hand side is the rf plasma anode (coil in the center of the vessel).

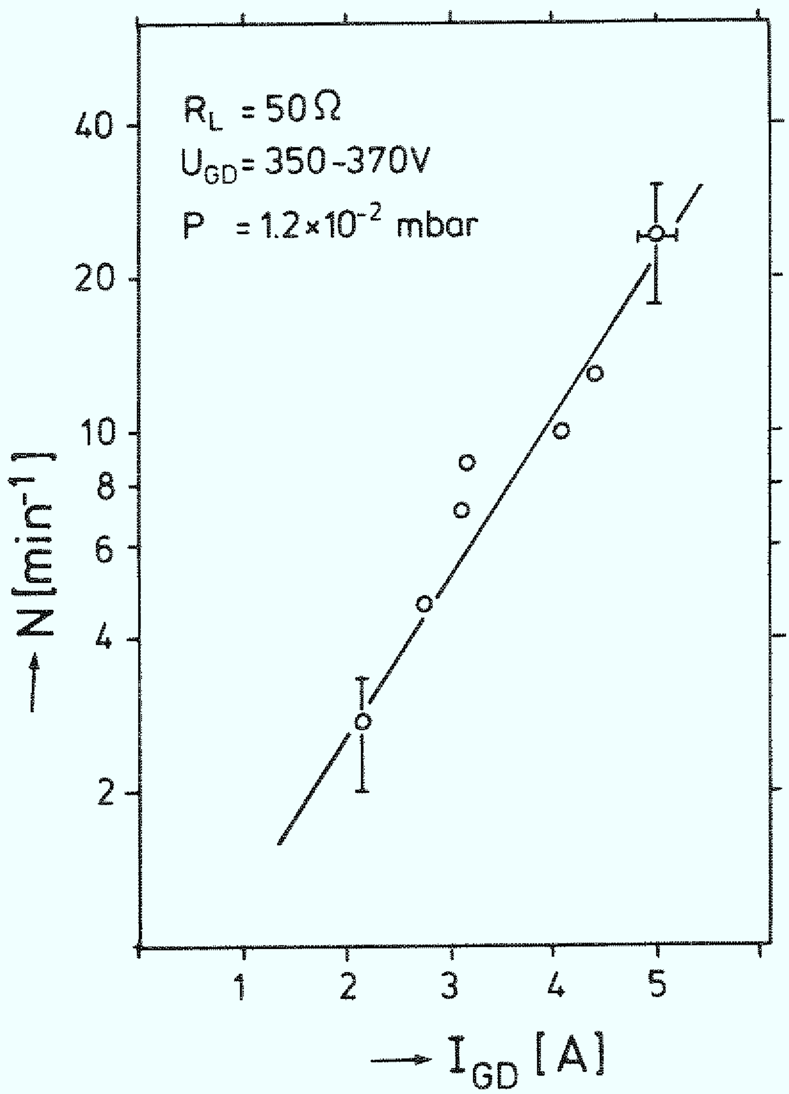

Fig. 17 Arcing frequency as a function of the discharge current I_{GD}

- During the later measurements with the Lecher antenna and with the coil antennas, another type of arcs has been observed. The luminescent spots were clearly separated from the anode. The arc was obviously fed by the wall-near plasma ("unipolar"). They struck across the cathode sheath. An example is shown in fig. 16. The arcs occured, irrespective which anode was used. The following comments refer to observations made on this "unipolar" arc behaviour.

The arcing probability depends sensitively on the current of the RG-discharge. For fixed plasma parameters it decreases as a function of time (III.3.3). No unique dependence on the pressure in the discharge was identified. Since the plasma parameters vary with pressure, it is difficult to separate its influence from other effects. Fig. 17 shows how the arcing frequency varies with the current I (the voltage changed by about 20 V in the range of I covered). Although the data points are scattered, an exponential dependence is suggested (cf. also /6/).

The occurence of the arcs was very markedly localized along the welds of the vessel. The arcs did not show up preferentially at edges of the apparatus like portholes or tubes .

The duration of an arc extended up to about a second in the initial phase and at elevated glow currents ($\sim$ 3 A). During this time they travelled sometimes about 1 m along the main welds of the vessel. The plasma resistance became very small. The arc current was then limited by the load resistor and the DC voltage applied. Later in the conditioning phase (III.3.3) the arcs became shorter and carried less current, even when the glow current was large.

The arc tracks in the smaller portholes (all ports shows similar patterns) have been investigated (figs. 18a,b). The tracks start at the flange weld and are particularly dense along the longitudinal weld. Not all tracks extend up to the end of the porthole, but a very pronounced longitudinal orientation can be seen+). It is interesting to note, that no arc track was observed on the antenna structures themselves, in the triangular Lecher-port, or on the endflanges of the antenna devices. These parts had all been treated by routine UHV-prehandling methods. In the main tank which due to its size

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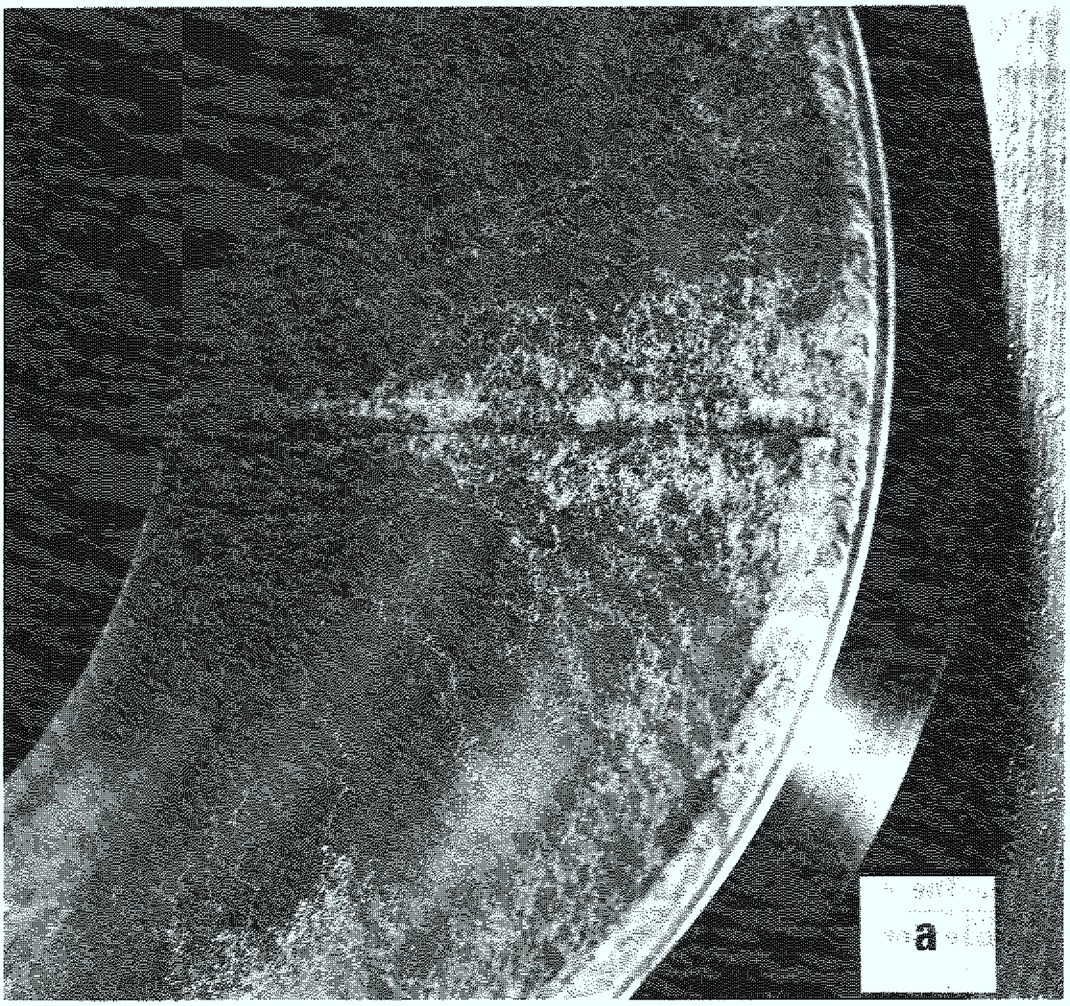
+) It is quite unlikely that the small rf-magnetic field might have induced this preferential orientation.



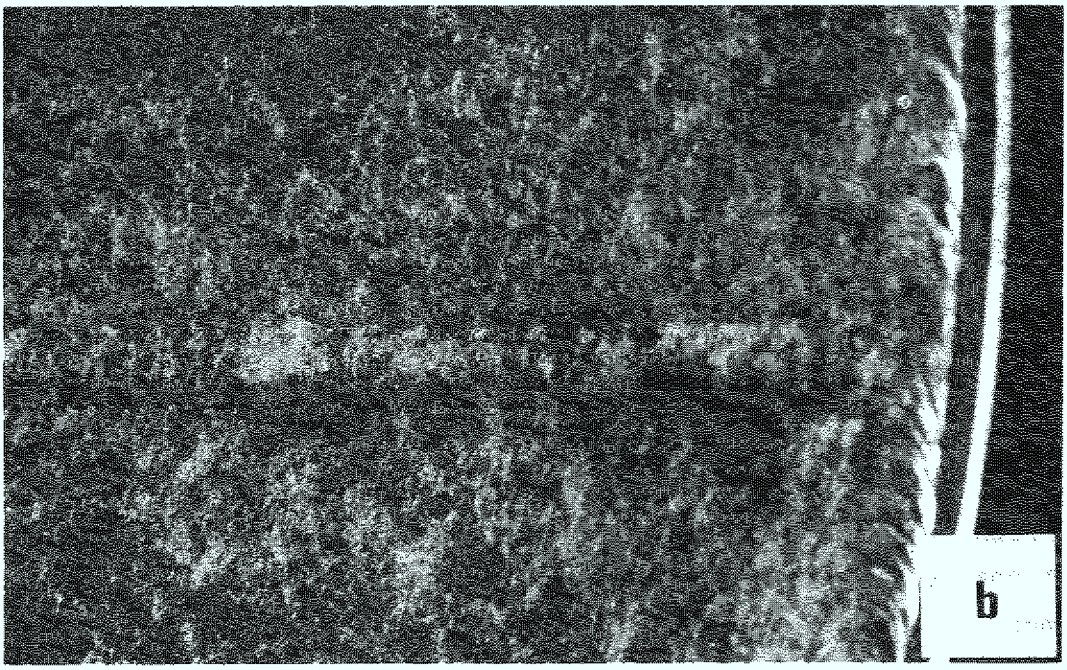


Fig. 18 Arc tracks in the neighbourhood of the main weld of a NW 250 porthole (a) and enlarged section of the same figure (b).

could not be cleaned as carefully, arcs occured at coldworked (strongly bent) structures. Here and at the welds residual organic materials from the prehandling procedure of the vessel probably triggered the arcs. The materials evaporate at much lower temperature than the metal and are easily ionized later under the influence of the arc. The evaporation might give rise to a local density increase, which is large enough to initiate the arc. The later evaporation of metal and of further organic material would make it move along the surface like a spark on a firing tape.

In the absence of a strong magnetic field the preferential direction of the tracks would be along "surface defects" such as microcracks from the manufacturing and machining process and the prorous structure of the weld. Both could act as reservoirs for material which is easily evaporated.

III.3.3. Conditioning

For fixed discharge parameters, the arcing frequency decreases as a function of time. As can be seen from figs. 19 - 20, an exponential dependence is suggested. This agrees with the observations of Mioduszewski et al /12/ on microarcing in an rf plasma. Fig. 20 also shows that after a conditioning period at a glow current of 3A, a decrease of this current down to 2.5 A results into a very large reduction of the arcing frequency. The decrease is much larger than the preceding increase of the arcing rate which occured when the current was increased from 2.5 to 3 A.

Thus RG- or a glow-discharges could be used to burn out possible arcing sites in (non bakeable) fusion devices before main discharges are initiated. The procedure is well adapted to this purpose because of the high cathode sheath potential. The treatment should be carried out in such a way that the current of the discharge is gradually and carefully increased up to the desired value. It may be useful to choose a pressure for the "arc-conditioning-discharge" which differs from that of the "cleaning-discharge" in order to optimize the cathode fall potential. The authors believe however that bake-out procedures, when applicable, should be preferred.

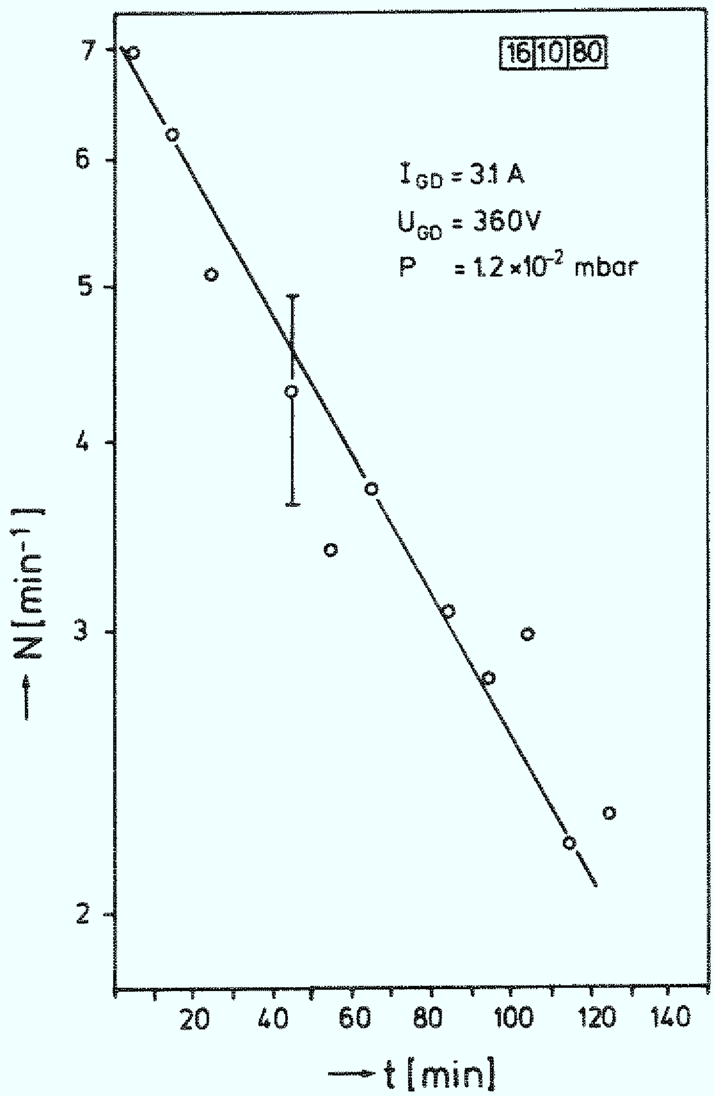


Fig. 19 Arcing frequency as a function of time. Before these measurements several modifications of the apparatus were made and a prolonged air exposure resulted.

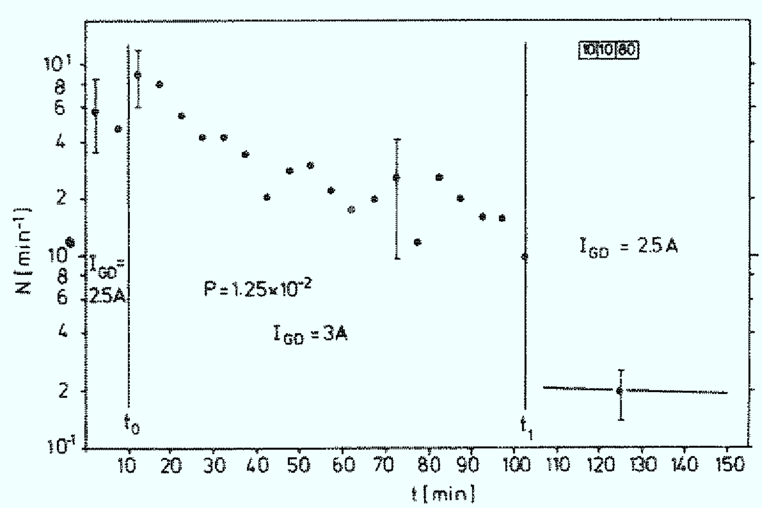


Fig. 20 Arcing frecency as a function of time. The discharge current was increased from 2.5 A to 3 A at t_0 and brought back down to 2.5 A at t_1.

III.3.4. Control of arcing

Continuously burning bipolar arcs, which would concentrate large power densities onto small wall areas for prolonged periods of time, have never been observed in the low pressure domain and even in the high current range explored here. Thus it does not seem to be necessary to develop special means against their occurrence at least as long as the discharge is operated at total currents of ten amperes or below. If a discharge were to be operated at very high total currents (e.g. in an extremely large vessel), it might be useful to monitor the glow current and to switch off the DC (not the rf) power supply when the duration of the current spike produced by the arc exceeds some preset value. An advantage of the RG discharge is that, when the DC voltage is reapplied, the glow current flows again without the necessity of pressure manipulation.

It is difficult to control unipolar arcs, once triggered because of their short duration. It is however desirable to limit their current in order to minimize the material erosion. Since the current of the unipolar arc is fed by the capacitance of the wall-near plasma layer, a distribution of the discharge current over several anodes having separate (large) load resistors cannot help much in this respect. Our measurements indicate, that for arcs of long duration, the total arc current is limited by the ratio U/R_L^e where R_L^e is the equivalent load-resistance of the parallel anode circuits. A large inductance in series with a purely ohmic load resistor could here limit the arc current down to a value which is close to that of the total steady state current of the discharge.

As observed previously /5/, it is again confirmed that a thorough degreasing and cleaning of the vessel reduces the arcing probability. Moreover, as mentioned in the introduction and in /5/, in situ bake-out procedures have proven to be very effective in avoiding the appearance of arcs in RG discharges.

IV. Conclusions

The ignition and quenching pressures of RG discharges in hydrogen werein the anode is supported by a low power rf discharge are lower than those of pure glow discharges. The reduction factor found here is ~ 3. The effect is not very sensitive to the rf system used (inductive or Lecher line). Low operating pressures are desirable /5/ to achieve high discharge cleaning efficiencies.

As expected, it has turned out to be easier to operate the RG discharges at low gas pressures when the size of the vessel was enlarged. The lowest ignition and quenching pressures are achieved when the anode is positioned at the centre of the vessel which acts as a hollow cathode. In tokamaks, this requires however retractable anode systems.

The discharges can also be sustained by fixed RG anodes located in portholes, but only at higher pressures ($P_Q = 2 \times 10^{-3}$ mbar); this affects the cleaning rate. The anodes should, as far as possible be positioned near the main volume and in broad portholes.

The total current can be distributed among several anodes by proper choice of the load resistors. This presents advantages in a toroidal vessel, and simplifies the cooling problems. It was however observed that, when the pressure was reduced, each RG anodes quenched at its own P_Q value.

The RG discharge can easily be ignited by the injection of a gas puff in the vicinity of an rf antenna.

The occurence of bipolar arcs could only be observed in the very initial phase of this work and when the discharge was operated at large currents. They disappeared after a few minutes and could not be reinitiated using the available experimental means. Thus special provisions for the stabilization against columnar arcs do not appear necessary at total currents around 10 A. In very large devices it may be useful to monitor the current and switch the DC power supply off in case of a continuous arc. During the later phases unipolar arcs occured, preferentially at contaminated parts of the surface. Their frequency increases nearly exponentially with the discharge current. In agreement with earlier results /12/ it was measured that the unipolar arcing rate decreases exponentially with time at fixed plasma parameters.

A thorough cleaning and degreasing, a bake-out at $T \approx 200\ ^{o}C$ /5/ or a gradual increase of the current (making use of the conditioning effect) should allow to avoid unipolar arcing problems in RG cleaning discharges.

V. Acknowledgements

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