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## Abstract

Current disruptions are investigated in a magnetized plasma column with an inductive external electric circuit. It is found that they persist in spite of the fact that each disruption gives rise to a large inductive over-voltage. This drops off at an electric double layer formed in the plasma where most of the magnetic energy, initially stored in the circuit inductance, is released as particle energy.

Simultaneously as the current disrupts, the potential level at a local potential minimum in the plasma decreases. This is expected to cause the disruption by reflection of electrons.

## 1. Introduction

In low density plasmas spontaneous current "disruptions" may appear when the electric current density along the magnetic field is sufficiently large. Each disruption is characterized by a marked decrease of the current during a certain time interval, which typically is of the order of many ion plasma periods.

In spite of the relatively numerous observations of this phenomenon, the physical processes causing it are not very well-known. In most observations only the total potential drop over the plasma has been measured, and there seems to be only a few cases (Lutsenko et al. 1975, Torvén and Babić 1975, Iizuka et al. 1982, Stenzel et al. 1982, Torvén and Lindberg 1983) where the spatial distribution of the electric field has been investigated. In these cases the phenomenon has been found to be associated with electric double layers.

In this paper we present investigations of a magnetized plasma column when the external electric circuit is dominated by an inductance L. We find that the current disruptions persist in spite of the fact that the rapid decrease of the circuit current produces inductive voltage drops up to several hundred volts over the plasma. This voltage drop is concentrated to an electric double layer, formed within the plasma, where magnetic energy is released as particle energy. This type of energy transfer has been proposed for applications in cosmic plasmas (Alfvén 1981).

## 2. Experimental device and methods

The measurements are made in a triple plasma machine (Torvén 1982) consisting of a central chamber and two plasma sources, $S_1$ and $S_2$ (Fig. 1). Plasmas are produced in the sources by discharges between heated tungsten filaments and the cylindrical chamber walls. A cylindrical plasma column is obtained in the central chamber by inflow of plasma through the apertures $A_1$ and $A_2$. These determine the diameter of the column (3 cm) which is radially confined by a homogeneous axial magnetic field (11 mT). Since the aperture diameter is much smaller than the diameter of the main pump, a pressure difference can be maintained between the sources and the central chamber, when gas (argon) is let in at $G_1$ and $G_2$. Effects of impact ionization in the chamber are reduced in this way, and the plasma density there ($5.10^{15}$ $m^{-3}$) is controlled by the source discharge currents $I_1$ and $I_2$ (Fig. 1). The auxiliary electrodes $B_1$ and $B_2$ have not been used in this experiment.

The external electric circuit between $S_1$ and $S_2$ consists of a voltage source $U_o$ and an inductance L (110 mH). R (2.6 ohm) is the sum of the series resistance of the inductor and a shunt (1 ohm) for measurement of the current $I_L$. C (3 nF) is the distributed capacitance relative to ground of the plasma source $S_2$ and its electric supply circuits. The plasma current $I_{pl}$ is measured by means of another shunt (1 ohm).

Electric potentials are measured with axially and radially moveable electron emitting probes. These are operated close to floating potential by using high impedance voltage dividers (100 Mohm) to limit the probe current. The distributed capacitance (50 pF) of the probe and its heating circuit limits the time resolution. However, it should be noted that it is the dynamic resistance of the plasma, defined by the slope of the probe characteristic at floating potential, which is the relevant resistance determining the time resolution. In the present experiment this has values between 5 and 30 kohm, giving an upper cut-off frequency (3 dB) of at least 100 kHz. The floating potential of the emitting probe is lower than the plasma potential, but still it gives a good measure of the relative variation of the plasma potential in space and time. The same probes are also used as Langmuir probes.

The disruptions appear approximately periodically, and time-resolved potential profiles are obtained by boxcar averaging technique. To improve the reproducibility, the analogue output of a transient recorder, operated in the pre-triggering mode, is averaged.

## 3. Investigations of the disruptive plasma

Previous observations (Torvén 1982), without inductance, showed that stable double layers form in this device when a voltage ($U_o$) is applied between the sources, and that the potential drop across the double layer takes approximately the value of the applied voltage.

Also in the present experiments a steady double layer forms when no inductance is introduced in the circuit. However, when there is a large inductance in the circuit (0.11 H), periodic disruptions occur, and they become most regular when the sources are operated differently. Typical parameters are for $S_1$: p = 20 mPa, $U_1$ = 40 V, $I_1$ = 1.0 A (temperature limited), and for $S_2$: p = 100 mPa, $U_2$ = 17 V, $I_2$ = 3.5 A (space charge limited). When no current is drawn between the sources the plasma at z = 6 cm outside $A_1$ has $T_e \approx$ 11 eV, $n_e \approx 5.10^{15}$ $m^{-3}$, and at 6 cm outside $A_2$ (z = 54 cm) $T_e \approx$ 6 eV, $n_e \approx 10^{16}$ $m^{-3}$. (z is the axial coordinate; z = 0 at $A_1$, z = 60 cm at $A_2$.)

### 3.1 Plasma potential variations during a disruption

With no current flowing the potential distribution along the axis has a local minimum at z ≈ 10 cm. Between the minimum and $A_2$ there is an electric field accelerating electrons towards $S_2$. This potential distribution prevails also when a low voltage is applied and a steady current flows (e.g. $U_o$ = 20 V, $I_{pl}$ = 45 mA). When $U_o$ is increased to about 30 V, a threshold is passed and disruptions begin to occur sporadically. When $U_o$ is increased further, the disruption frequency increases and becomes regular, as in Fig. 2(a),(b),(c) for $U_o$ = 100 V. The shape and amplitude of the over-voltage pulses change only little with $U_o$. Between the pulses $U_{S2}$ is low compared with $U_o$.

It is seen in Fig. 2(a) that the potential of the probe $P_1$ (z = 56 cm) near $S_2$ closely follows the potential of $S_2$, while the potential of the probe $P_2$ (z = 49 cm) does not vary very much and in fact goes down a little. This shows that the whole inductive voltage drop during the disruption is taken up by an electric double layer, which is located between $P_1$ and $P_2$ all the time. Fig. 2(b) shows that the potential during a disruption drops also at z = 30 cm, but remains almost constant at z = 11 cm.

In Fig. 2(c) the plasma current, $I_{pl}$ and the current in the inductance, $I_L$, are compared. The difference $I_{pl} - I_L$ is the current to the unavoidable distributed capacitance, C. It is seen that $I_L$ goes down to below 20 percent of its initial value during a disruption, which means that 95 percent or more of the stored magnetic energy is transferred to the double layer and will be converted to particle energy.

Fig. 3 shows potential profiles along the axis in the left part of the experimental chamber, recorded at times before, during, and after a disruption. It is seen that the potential minimum becomes deeper during the disruption. As discussed further below the depth of this potential minimum is expected to control the plasma current during a disruption by reflection of electrons.

Fig. 4 shows corresponding potential profiles in the right part of the chamber, where the double layer appears. When the voltage builds up the double layer moves slightly toward $S_2$. This is in agreement with earlier observations on stationary double layers (Torvén 1982).

In the intermediate region, z = 32 to 43 cm, not covered by Figs. 3 and 4, the plasma potential continues to rise monotonically but with lower gradient than in Fig. 3 for most of the times, but during the interval t = 0 to 30 $\mu$s it goes down a few volts to another minimum in front of the double layer (z = 45 cm). The level of that minimum is however much above the minimum observed around z = 12 cm.

Sampled Langmuir- and emitting probe characteristics at $t = 20$ μs have been measured at three points, (a) $z = 4$, (b) $z = 12$ and (c) $z = 20$ cm (marked in Fig. 3). The characteristics at (a) and (b) indicate approximately Maxwellian distributions with (a) $T_e \approx 12$ eV, $n_e \approx 7.10^{15}$ $m^{-3}$, (b) $T_e \approx 12$ eV, $n_e \approx 2 \,.\, 10^{15}$ $m^{-3}$. At (c) the distribution is far from Maxwellian and the average energy is larger than at (a) and (b). The saturation probe current is about half of that at (b). Electrons are obviously accelerated in the region of high electric field between (b) and (c), which may be regarded as a weak double layer.

Characteristics recorded at $t = 40$ μs do not show a high average energy at (c) consistent with the smaller electric field between (b) and (c) at that time.

3.2 Time averages of potential and current

Time averages of the plasma potentials at six different points along the axis are recorded in Fig. 5(a) as functions of the applied voltage, $U_o$, which is swept slowly. The average current is recorded in Fig. 6(b). The average plasma potentials at z = 11, 20, 30 and 49 cm rise slowly with $U_o$ up to the threshold value, $U_o \approx 28$ V, and then saturate at lower values when $U_o$ is increased further. The average current also saturates at the threshold and then reduces a little.

The average potentials at z = 56 and 58 cm on the contrary increase linearly with $U_o$, and the average potential difference between $P_1$ and $P_2$ is equal to the average potential drop across the double layer. This increase is essentially due to the increasing frequency of the disruptions, because the inductive voltage pulses have approximately the same shapes and amplitudes for different $U_o$, and the potential between the pulses is low and gives a negligible contribution to the time-average.

3.3 Discussion

According to Figs. 2(a)-(c) the current drops during the whole over-voltage pulse, and simultaneously the potentials at $P_2$ and $P_3$ decrease and reach their lowest values at the end of the over-voltage pulse, i.e. at the current minimum. The potential level at the minimum in the profiles given in Fig. 3 behaves in the same way. The plasma sources are very little affected by the plasma in the central chamber, and the electric current is supplied essentially by electrons from $S_1$, because the rapidly increasing double layer voltage drop should prevent electrons from $S_2$ to reach the potential minimum. Accordingly, the increasing depth of the minimum should cause the disruption by reflection of electrons, and the minimum should act essentially as a virtual cathode (Nezlin 1964).

Such a behaviour of localized potential dips has been observed in numerical simulations, and a model equation describing the deepening of the dip has been proposed (Chanteur et al. 1983, Nishihara et al. 1982). In other simulations "explosive" double layers, appearing recurrently with life times up to a few ion plasma periods (Belova et al. 1980) have been observed. Effects from the external electric circuit have also been simulated (Sato and Okuda 1981, Smith 1982). We believe that there are interesting connections between our experiment and these numerical simulations, and we expect that further investigations will demonstrate this. However, three-dimensional effects may also introduce important differences between the simulations and the experiment.

Once the double layer has formed, another mechanism may also be of importance for the current disruption. When the potential drop of the double layer has reached a level of some tens of volts, all the ions from $S_1$ are reflected at the layer. Ions from $S_2$ are accelerated in the layer and enter the plasma with a high velocity. If the flux of ions from $S_2$ is constant, the density of ions in the plasma on the low potential side of the layer will consequently decrease. Then quasineutrality requires a decrese of the electron number density, too, as is observed at the potential minimum.

As already mentioned (Sect. 3.1), another weak potential minimum also exists just in front of the double layer (z = 45 cm), and its role in the current disruption process should also be investigated.

Between two over-voltage pulses the current rises slowly (Fig. 2). The voltage induced in L is then negative and keeps $U_{S2}$ low: $U_{S2} = U_o - L\, dI_L/dt$, and the current is regulated by the low value of $U_{S2}$. This pre-phase of a disruption can be seen as a slowly increasing $U_{S2}$ in Fig. 2. Already in this phase a deepening of the potential minimum is seen in the profiles, Fig. 3, t = -40 to 0 µs.

Finally the point of current saturation is reached and dI/dt approaches zero. Then $U_{S2}$ rises to $U_o$ at a rate limited mainly by the capacitance to ground, C. The current starts to decrease due to the deepening of the potential minimum which causes the induced over-voltage pulse. The voltage is in good agreement with the observed $dI_L/dt$, and the formation of the double layer should be caused by the induced voltage at $S_2$.

4. Disruptions in different external circuits

In all the experiments described hitherto we have used L = 0.11 H and C = 3 nF (stray capacitance). Experiments with other values have also been made. Increasing L to 1.0 H led to so high over-voltages that break-down (arcing) through the double layer occured before the voltage maximum. This is due to the relatively high pressure in $S_2$ in this experiment. To limit the inductive over-voltage we have also increased C and combinations of L = 0.05, 0.11, 0.21, 1.0 H and C = 3, 8, 16, 70 and 800 nF have been tested. An example, with L = 1.0 H, C = 70 nF, is illustrated in Fig. 6. Here the time scale is a factor of ten slower than in Fig. 2(a)-(c). The voltage pulse has nearly the shape of a half period of a sinuisoidal oscillation which ends abruptly with almost no over-swing like in Fig. 2(a)-(c). The current oscillogram is quite different. The current drops rapidly at first, at a rate similar to that in Fig. 2(a)-(c), and then slowly to a minimum which occurs before the end of the voltage pulse. At the end (e in Fig. 6) another downwards step to the absolute current minimum just after the end of the voltage pulse is very marked.

In a loss-free parallel resonance circuit a sudden complete interruption of the current would produce a sinusoidal oscillation with the voltage amplitude $U = I_o \sqrt{L/C}$ and period $T = 2\pi\sqrt{LC}$. Presence of losses would increase the period a little and the oscillations would be damped. For the LC-combinations tested we find the shape of the voltage pulse similar to a half period of a sine-wave with a duration of about 1.1 - 1.4 times the half-period for the undamped circuit. The amplitudes are found to be 0.3 to 0.6 times the one calculated for an undamped circuit. This suggests that we should make a distinction between the time of current decrease, defined as the time during which the current decreases rapidly in the beginning of the disruption, and the duration of the over-voltage pulse. In Fig. 2(a)-(c) these are approximately equal, but for large LC-values they become quite different. The time of current decrease is, however, of the same order in the two cases. It can be expected to depend mainly on processes in the plasma, such as ion transport times, but also to some extent on the rate of rise of $U_{S2}$.

The duration of the over-voltage pulse on the contrary, is mainly determined by the resonance period of the circuit $T/2 = \pi\sqrt{LC}$. When this is much longer than the time of current decrease, the effect of the disruption is to switch from one state of low voltage and comparatively high current to another state of lower current, with a double layer taking up the voltage. The behaviour of the plasma in this state is what can be expected from its static characteristics (Torvén 1982), i.e. a double layer with a voltage determined by the circuit voltage is maintained until most of the energy initially stored in the inductance is transferred to the double layer. The over-voltage pulse is initiated during the time of current decrease. The current does never go to zero but to a low value approximately corresponding to the static double layer voltage-current characteristic.

The sudden end of the over-voltage pulse is remarkable. The voltage goes to a low, stationary value almost without over-swing. Only a negative over-swing of a few volts can be seen when the oscilloscope amplification is increased. At this time a sudden step-down in the current can be seen, g in Figs. 2(c) and 6. If the voltage decreased further, it would imply a reversal of the current, i.e. electron emission from $S_2$, which could become large already at a low reverse voltage since the electron density in $S_2$ is higher than in $S_1$. Reversal of the current has, however, not been observed in the present experiments.

## 5. Conclusions

When the electric field applied to a plasma column in an inductive electric circuit exceeds a certain threshold value spontaneous current disruptions are excited. A disruption produces an inductive over-voltage in the external circuit, which drops off at a double layer in the plasma.

The energy initially stored as magnetic energy in the inductance is transferred to particle energy in the double layer. Under suitable conditions more than 95% of the energy can be transferred in this way.

Simultaneously as the current disrupts, the potential level at a local potential minimum in the plasma decreases. This is expected to cause the disruption by reflection of electrons.

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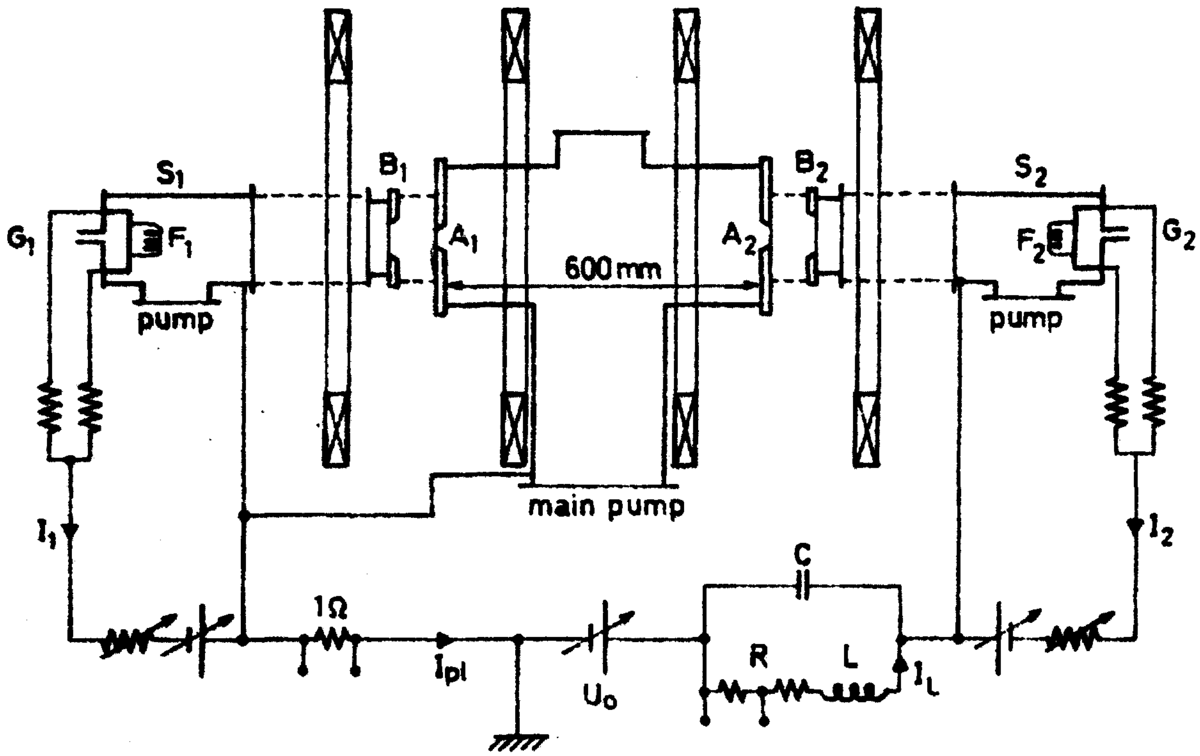


Fig.1. Schematic picture of the experimental device.
A plasma column is maintained in the central chamber between $A_1$ and $A_2$ by inflow of plasma from the sources $S_1$ and $S_2$. ---- glass, ——— stainless steel.

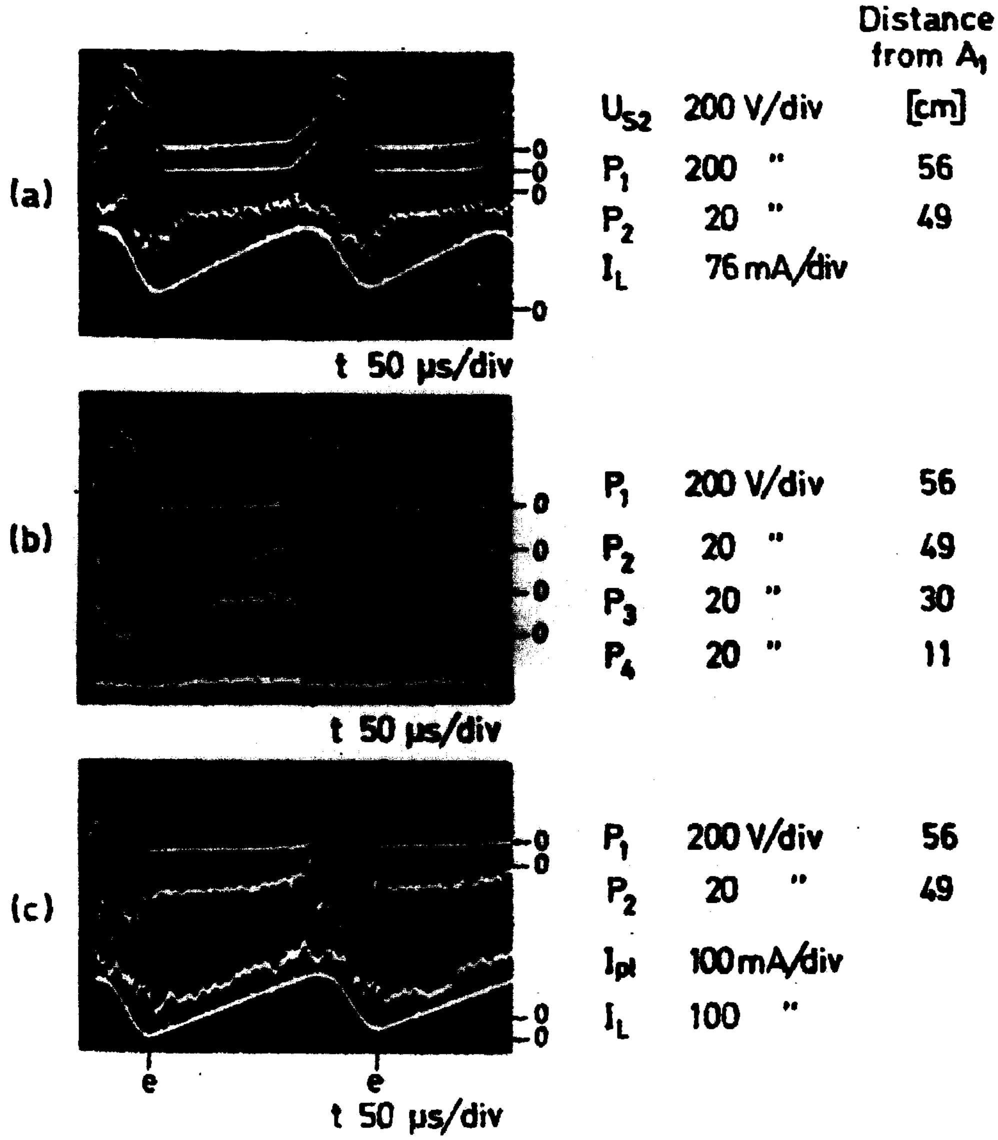


Fig.2. (a) Periodic current disruptions (lowest trace) showing the potential variations of $S_2$ and of two emitting probes $P_1$ ($z$ = 56 cm) and $P_2$ ($z$ = 49 cm), separated by 7 cm ($z$ is the coordinate measured from $A_1$).
The inductive voltage (350 V) appears as a potential drop across a double layer in the plasma between $P_1$ and $P_2$. The zero levels are marked in the same order as the traces. $U_o$ = 100 V, $I_{pl}$ = 105 mA.

(b) Same conditions as (a) but with two more probes; $P_1$ ($z$ = 56 cm), $P_2$ ($z$ = 49 cm), $P_3$ ($z$ = 30 cm) and $P_4$ ($z$ = 11 cm). $P_3$ and $P_2$ show a potential dip of about 20 V whose leading edge is seen to propagate towards $S_2$ with a velocity of about $10^4$ m/s, while the potential of $P_4$ remains about constant. Compare Fig.3.

(c) Same conditions as (a) and (b). The potentials of $P_1$ and $P_2$ are shown together with the plasma current, $I_{pl}$ and the current in the inductance, $I_L$. Note a sudden decrease in the current (marked e) at the end of the over-voltage pulse.

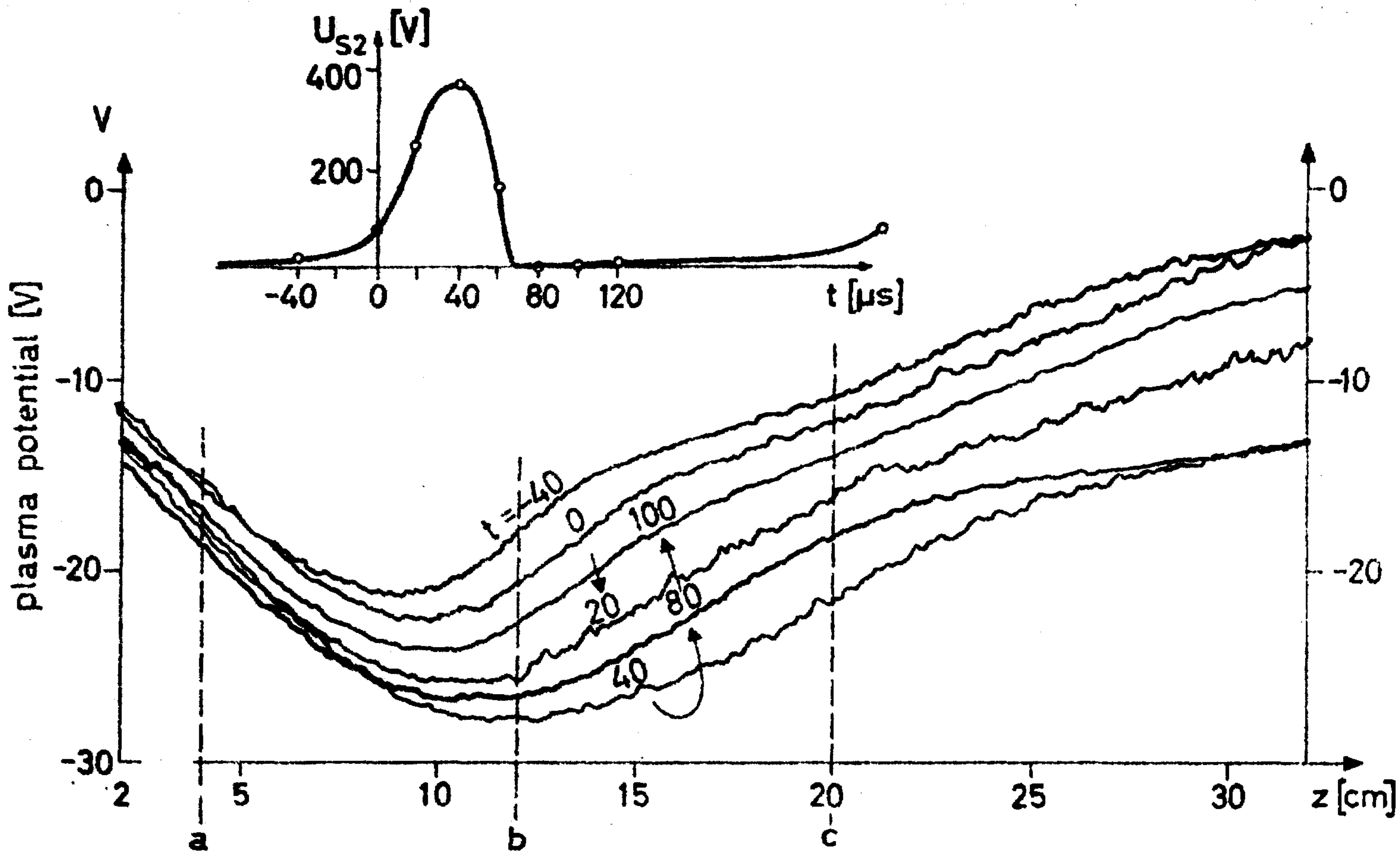


Fig.3. Potential profiles along the axis in the left part of the experimental chamber at times before, during and after a disruption. The times are indicated by open circles in the inserted oscillogram of a disruption voltage pulse. The curves were obtained by sampled measurements of the floating potential of an emitting probe. Sampled Langmuir probe measurements were made at the points, a,b,c.

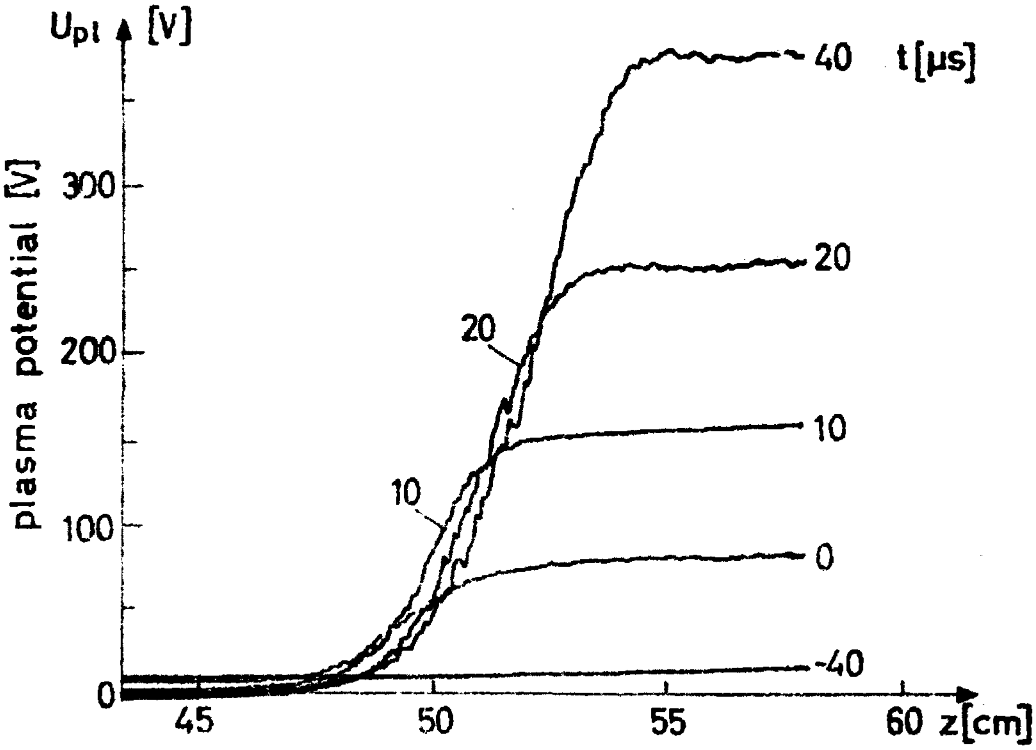


**Fig.4.** Potential profiles showing the double layer in the right part of the experimental chamber at times before and during the build-up of a disruption (cf. Fig.3). The transition from low to high potential is seen to take place within 5 cm or less.

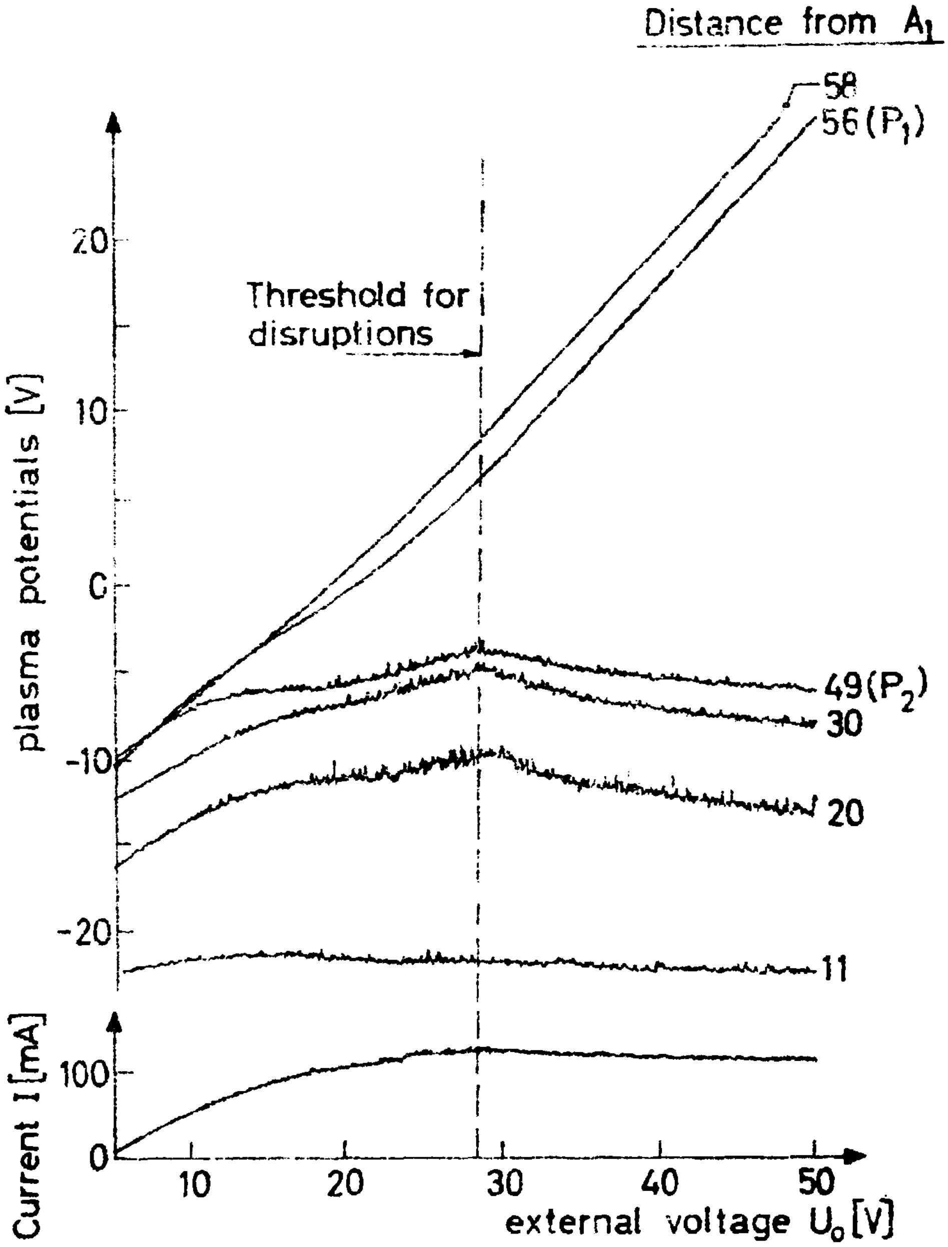


Fig.5. (a) Time averages of the potential variations at six different distances from $A_1$ when the applied d.c. voltage $U_o$ is varied slowly. At the threshold for disruptions, $U_o \approx 28$ V, disruptions begin to occur sporadically. When $U_o$ is increased further, the frequency of disruptions increases while the wave-forms of each disruption remains approximately the same. For each disruption a transient double layer is formed between the probes $P_1$ and $P_2$. The probes between z = 11 and 49 cm indicate a monotonic electric field directed towards $A_1$.

(b) Time average of the current $I_{p1}$.

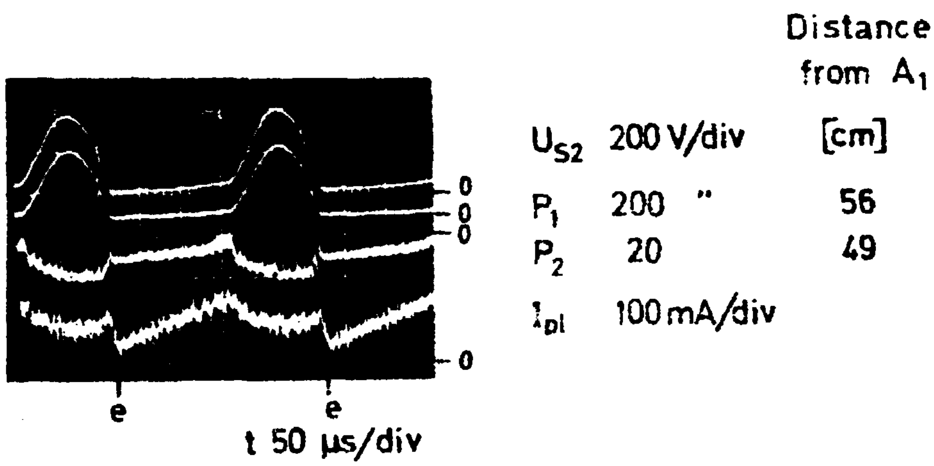


Fig.6. Oscillograms from an experiment with increased L and C. L = 1.0 H, C = 70 nF. The double layer is maintained during the whole voltage pulse, which has a duration 1.25 times the half period of the undamped LC circuit. $U_o$ = 100 V.

The plasma current oscillogram is quite different from Fig. 2(c), and the negative step at e is very marked.

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Key words: Double layer, Current disruption, Current limitation, Energy transfer