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ON THE SPOKE STRUCTURE IN CRITICAL VELOCITY ROTATING PLASMAS

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Abstract

The ionizing front model for the current spokes in homopolar experiments on the CIV phenomenon is briefly reviewed, and the main predictions are compared to experimental observations. It is concluded that the proposed mechanism of localized electron heating at the leading edges of the spokes is well supported by the observations, but that there is a discrepancy about the sheath thickness, and about the location of the observed hf emission in relation to the space charge structure. The observed spokes have a thickness which exceeds the limit of applicability of the ionizing front model by typically a factor of ten. A new finding here is that the azimuthal electric field is closely proportional to \((n_e - \langle n_e \rangle)\), where \(\langle n_e \rangle\) is the average density. This relation holds on both sides of the density spokes, and also between the spokes, in spite of the fact that the electron temperature, current density, and hf emission are all strongly peaked about the leading spoke edge. This indicates that the mechanism which maintains the space charge structure depends mainly on the plasma density, and only indirectly on the ionization rate. It is proposed that a density-related partial blocking of the azimuthal Hall current could give the observed correlation between azimuthal electric field and plasma density.
1. Introduction

The ExB discharge geometry has for over 20 years been one of the most important for laboratory studies of the critical ionization velocity (CIV) effect. In spite of this, the discharges are still incompletely understood; only the early theories for homopolar discharges (Sokhol, 1968; Lin, 1961; Drobyshevskii, 1964; Lehnert, 1966) aimed at complete descriptions of particle, momentum and energy balance. These theories could explain the experimental results only in a limited parameter range; also, they did not take account of the spoke structure which was later (Himmel et al., 1976) found to be casually connected to the CIV phenomenon. Raadu (1978) made a theory for Axnäs's (1972) ExB discharge in the coaxial plasma gun geometry. He used a classical treatment of particle and momentum balance, while the energy equation was replaced by a semi-empirical assumption intended to account for the CIV effect. The theory was only partially successful. In particular, it predicted axial electric fields (i.e., the field component directed along the plasma flow) which were a factor 3-7 higher than the observed fields. A possible reason for this discrepancy might be that particle velocities were derived from classical momentum balance; later experiments by Axnäs (1988) have shown that both ions and electrons have anomalous drift velocities in the coaxial plasma gun.

The most recent theory for the homopolar CIV discharges is the ionizing front model by Piel et al. (1978, 1980). This theory does not treat the whole discharge, but is limited to the leading edges of the current spokes. We will here briefly review this theory and compare it to the experimental observations.

2. The model of Piel, Möbius and Himmel.

The model of Piel et al. (1978, 1980) is schematically shown in Fig. 1. It is drawn in the plasma frame, with the neutral gas streaming from the left with a velocity $v_c$. The electrons are trapped on the magnetic field while the ions overshoot in the positive y direction. The potential drop $\Phi_0$ over the sheath is determined by the assumption that the ions are reflected by the electric field rather than by the Lorentz force,

$$e \Phi_0 \geq \frac{1}{2} m_i v_c^2,$$

and the sheath thickness depends on the spatial scale of the region of ionization. If the ionization region is extended, an upper limit to the sheath thickness is the ion gyro radius,
Fig. 1. Particle orbits in the space charge sheath (from Piel et al., 1980).

\[ D_{\text{max}} = \rho_{gi} = \frac{v_c}{W_c} . \]  \hspace{1cm} (2)

In the special case when the ionization is limited to a thin region at the left edge of the sheath \((n_e/\Delta n_e \ll \rho_i)\) the inequality in Eq. (1) can be replaced by an equality. This is the "thin sheath" case. The sheath thickness in the "thin sheath" case obtains a minimum value estimated by Piel et al. (1980) to be

\[ D_{\text{min}} = \left( \frac{m_i v_c^2 e_0}{2 n^* e^2} \right)^{1/2} , \]  \hspace{1cm} (3)

where \(n^*\) is the average density of newly generated ions within the sheath. This thickness is close to the "newly generated ion Debye length" \(D = \lambda_D = v_c/\omega_{pi} \cdot \) Eq. 3 can be combined with \(n^* = n_e^* t_D\), where \(t_D = 4D/v_c\) is the time an ion spends in the sheath (both relations are taken from Piel et al., 1978), to give the sheath thickness

\[ D_{\text{min}} = v_c \left( \frac{m_i e_0}{8 v_i n_e e^2} \right)^{1/3} , \]  \hspace{1cm} (4)

where \(v_i = <\sigma_i v_e> n_i\) is the ionization frequency per electron.

In the ionizing front model there is a secondary Hall drift of electrons perpendicular to the direction
of the plasma flow. This drift provides the electron contribution to the discharge current in a manner analogous to the axial electric field in Raadu's (1978) model for the coaxial plasma gun. Apart from carrying the discharge current, this secondary electron drift has another important role: the relative ion-electron drift in the radial direction is proposed to drive the modified two-stream instability, which in turn heats the electrons to energies above the ionization threshold.

2. Experimental observations.

Figure 2 shows experimental results: the ion current to, and the floating potential of, a symmetrical double probe in the Bochum I homopolar (from Piel et al., 1978). The ion current gives a measure of the plasma density. The model outlined above is proposed to apply to the density increase at the leading edge of the spokes (the region marked "1" in Fig. 2). The size of this region is 40 - 50 mm, which is much larger than the "thin sheath" thickness of Eq. 4, which turns out to be as small as 0.06 mm. (This calculation was made using an ionization frequency \( v_i = 10^6 \text{ s}^{-1} \) in accordance with the observed rate of density increase in Fig. 2.)

There are several points of agreement between the model of Piel et al. (1978, 1980) and the observations of Fig. 2: The potential across the observed sheath is 100-150 V, which is considerably above the ionization potential of helium, 24.5 eV. This agrees with Eq. 1 for a sheath

![Graph](image-url)

Fig. 2. Floating potential and ion current to a double probe (from Piel et al., 1978).
where the "thin sheath condition" \( n_e/\Delta n_e \ll \rho_{gi} \) is not fulfilled. The force on the ions, \( eE \), at the peak value of the measured azimuthal electric field (\( 10^4 \) V/m) is of the same order as the Lorenz force \( ev_cB \); the azimuthal electric field therefore plays an important part in accelerating the new ions to the plasma's rotation velocity. Finally, the azimuthal distribution of the radial current was measured by magnetic probes. The current was found to be flowing mainly in the leading edge of the spokes, in agreements with the ionizing front model. Both the magnitude and the spatial extent of the current sheaths agree with the interpretation that they are carried by electron Hall drift in the observed azimuthal electric field. The radial electron-ion drift inferred from the current density was sufficiently large to excite the modified two-stream instability.

However, there is a clear discrepancy about the size of the structure: the density increase is spread out over 40 - 50 mm, while the ion gyro radius is 5 mm. The observed structure therefore exceeds the upper limit \( D_{max} = \rho_{gi} \) for the sheath thickness (Eq. 1). This has serious consequences for the particle motion: the mechanism which produces differential electron-ion drift along the sheath in Fig. 1 works only for sheaths where \( D < \rho_{gi} \). When \( D >> \rho_{gi} \), a differential drift (the classical Hall current) occurs only when the ion Hall parameter \( \omega_{gi}\tau_{coll} \) is below unity. In the experiment of Piel et al. (1978, 1980) this is the case: \( \omega_{gi}\tau_{coll} \) lies in the range 0.1 - 1.

![Fig 3](image-url) An approximation to the potential of Fig. 2, and the time derivative of that curve.
Fig. 3 shows a remarkable property of the experimental curves of Fig. 2: the upper curve in Fig. 3 is an approximation of the potential of Fig. 2, and the lower curve is the derivative of that curve. It is clear that this lower curve follows the measured density curve of Fig. 2 (the reader is encouraged to hold pages 5 and 6 towards the light and check this). Consequently, the density in Fig. 2 closely follows the time derivative of the potential. For a steady rotating structure, the induced electric field vanishes, and also $dU/dt$ is proportional to $dU/d\xi$, which is proportional to the electrostatic field $E_\xi$. Therefore, the azimuthal electric field is proportional to the deviation from average plasma density,

$$E_\xi = K (n_e - <n_e>)$$,  \hspace{1cm} (5)

where $K$ is a proportionality constant, $\xi$ is the azimuthal coordinate in the direction of rotation, and $<n_e>$ is the azimuthal average of the plasma density. According to Fig. 3 this relation holds very well on both sides of the spokes, and also between them. This indicates that the same type of mechanism determines the azimuthal electric field in the whole discharge; it also seems that the important quantity is the plasma density and only indirectly the ionization rate.

Unfortunately, Fig. 2 contains the only published simultaneous measurement of plasma density and potential from these homopolar experiments. Fig 4 shows a later measurement which indirectly supports Eq. 5, and at the same time demonstrates another important result. The bottom curve of the upper panel shows the ion saturation current to a double probe, which reflects the plasma density. The bottom curve of the lower panel shows the floating probe potential. The upper curves in both panels show the same quantity: a wide band hf emission, which occurs in narrow bursts correlated to the leading edges of the spokes. The arrows in Fig. 4 have been added to Nickenig and Piel's (1987) original figures in order to clarify the correlation.

Inspection of the upper panel of Fig. 4 shows that:

1. A burst of hf occurs always when the density has dropped to a critical lower level, indicated by the dotted line (the inverse causality is not always true).
2. After this hf burst, there is a density increase, usually in proportion to the size of the preceding burst.

These observations clearly support the ionizing front model in the sense that the front of the spokes
is associated with strong wave activity, and that this wave activity is associated with some electron heating mechanism which explains the following plasma density increase. Of more interest here, however, is the timing with respect to the floating potential structure, shown in the lower panel of

![Graph showing hf emission with plasma density and floating potential](image)

**Fig 4.** Comparison of hf emission with plasma density and floating potential (from Nickenig and Piel, 1987).

Fig. 4. According to Eq. 5, any structure which is associated with a minimum in plasma density (as the hf bursts) should be connected to a minimum in $E_\phi$, i.e., a negative time derivative in potential. This seems also to be the case: the hf peaks have a tendency to fall a bit before, or at, the minimum of the potential. In the ionizing front model of Fig. 1 one would expect the opposite correlation: the observed hf bursts should have been observed in the maximum positive time derivative of the
potential.

3. Discussion.

Although the ionizing front model explains several of the observed features of the homopolar spokes, there seems to be some remaining discrepancy, particularly concerning the size of the space charge sheath, and the direction of the azimuthal electric field at the time of hf emission.

In a structure where the space charge sheath is extended over several ion gyro radii, the sheath electric field cannot be upheld by the ion dynamical effect indicated in Fig. 1. There is however the possibility that the azimuthal electric field is maintained by a closely related effect described by e.g. Alfvén and Pålthammar (1963) and Drobyshhevskii et al. (1970), where the governing parameter is the azimuthal variation in Hall conductivity. Consider an azimuthal density perturbation, initially without any azimuthal electric field. Unless \( \omega \tau >> 1 \) for the ions, a radial electric field would initially give the electrons a higher azimuthal velocity than the ions. Around a local density maximum, space charges would arise with an azimuthal electric field directed so as to stop the ion-electron separation and accelerate the ions forward with the electrons (Drobyshhevskii et al., 1970). This azimuthal electric field would also give a Hall current contribution in the direction of the original (radial) electric field.

We can tentatively extend this mechanism to the whole discharge by assuming that the electrons everywhere are displaced the same azimuthal distance with respect to the ions. The local space charges would then be proportional to the density gradient \( \frac{dn_e}{d\xi} \) (where \( \xi \) is the azimuthal coordinate in the direction of rotation). The situation is illustrated in Fig. 5.

Fig. 5. Ions lagging behind the electrons gives an electric fields correlated to the density.
The space charge is also (from Poisson's equation) proportional to \( \frac{dE_\xi}{d\xi} \); for a steady rotating structure, \( \int_0^{2\pi} E_\xi d\xi = 0 \), and we recover Eq. 5,

\[
E_\xi = K (n_c - < n_c>).
\]

The mechanism outlined above gives only the proportionality; it is possible that the actual value of \( E_\xi \) could be determined by particle and momentum balance, in a manner resembling Raadu's (1978) model for the coaxial plasma gun. Although the geometry is somewhat different between the homopolars and the coaxial system, it is suggestive that the observed range of azimuthal/radial electric fields (in the high-density part of the spokes in Fig. 2) is very close to the range axial/radial field (0.5-1) in Raadu's (1978) model.

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Key words: Critical velocity, critical ionization velocity, Alfvén's critical velocity, plasma-neutral gas interaction, homopolar discharges, current spokes.