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Transient Current Collection and Closure for a Laboratory Tether

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Abstract. The motion of tethered electrodes creates time-varying plasma currents. A similar current system has been studied in a large laboratory plasma with a stationary, pulsed tether. It is shown that in the appropriate electron MHD regime, the transient current is transported in the whistler mode. The current exhibits helicity. The insulated tether induces electron Hall currents which provide the cross-field current closure. The transient current increases with voltage and exhibits no saturation at the Langmuir limit due to electron heating. Superposition of delayed pulses emitted from displaced tether positions predicts that tethered satellite currents close along a short whistler wing rather than a long phantom loop.

Introduction

When a charged conductor of diameter D moves through a stationary plasma with velocity $\mathbf{v}$ across a magnetic field $\mathbf{B}$, a current pulse of duration D/v is generated in each flux tube of the conductor. Since for TSS-1 the pulse duration ($\approx$ 2 ms) is much shorter than the ion cyclotron period ($\approx$ 30 ms), but much longer than the electron cyclotron period ($\approx$ 1 μs), the ions are effectively unmagnetized while the electrons are fully magnetized. This parameter regime is known as Electron MHD [*Kingsep et al*, 1990] and differs from ordinary MHD in several aspects. For example, the transient current is transported by the electron whistler mode [*Urrutia and Stenzel*, 1988]. Cross-field currents are predominantly electron Hall currents. The solution of Maxwell's equations and Ohm's law predicts helicity in the perturbed fields and flows, $\mathbf{A} \parallel \nabla \times \mathbf{A} = \delta\mathbf{B} \parallel \nabla \times \mathbf{B} = \mu\mathbf{J}$, [*Isichenko and Marnachev*, 1987]. Experimentally, the current density and the perturbed magnetic field are observed to form vortices or short flux ropes in the current channel of biased conductors [*Urrutia et al,* 1995]. Although the fields are essentially force-free [*Urrutia and Stenzel,* 1996], nonlinearities arise from electron heating [*Stenzel and Urrutia,* 1996] and ion acceleration [*Urrutia and Stenzel,* 1997]. In order to model the currents of a moving tether, the dc current is represented by a sequence of pulses and the motion by a succession of steps in space. Having measured the time-dependent fields/currents of one pulse at one tether position, we superimpose, with the help of a computer, a multitude of delayed pulses from displaced tether positions so as to generate the coherent wavefront emitted by the moving tether. Although the linear superposition by Huygen's principle cannot address the nonlinearities around the electrodes, it is highly instructive to demonstrate the distant current path and closure. The latter has been subject to various theoretical ideas, e.g. the "phantom loop" [*Penzo and Ammann*, 1989], which cannot be tested without costly free fliers. Our laboratory observations of "whistler wings" have stimulated supporting numerical simulations [*Zhou et al*, 1996; R.W. Schunk, private communication].

Experimental Setup and Techniques

The experiments are performed in a 1 m diam, 2.5 m long uniform, quiescent, magnetized afterglow plasma (7×10^{11} cm^{-3}, 1.4 eV, 20 G, 2.6×10^{-4} Torr Ar) shown in Fig. 1Fig. 1. Two tethered electrodes (1 cm diam disk and oxide-coated cathode) are connected by a 20 cm insulated tether wire $\perp \mathbf{B}_0$ and center-fed with a 50 V, 0.1 A, 100 ns pulse. The time-varying magnetic field, $\mathbf{B}(\mathbf{r}, t)$, produced by the pulsed current, is measured with a magnetic probe recording the three vector components vs time at a given position. Measurements are performed at 15,000 positions in a three-dimensional volume in repeated, highly reproducible experiments. From the digitally stored data, the current density is calculated, $\mathbf{J}(\mathbf{r}, t) = \nabla \times \mathbf{B}/\mu_0$. The displacement current density is negligible compared to the conduction current density, $\mid \epsilon_0 \partial \mathbf{E}/\partial t \mid / \mid ne\mathbf{v} \mid = \omega\omega_c/\omega_p^2 \simeq 10^{-5}$. Time and space-resolved Langmuir probe measurements yield the electron density, temperature and plasma potential. The tethered current system is studied on a time scale where all currents close within the uniform plasma without interacting with boundaries. However, in experiments on current collection and I-V characteristics, the positive collector is tethered to the chamber wall which supplies a much larger return current than the temperature-limited electron emitter.

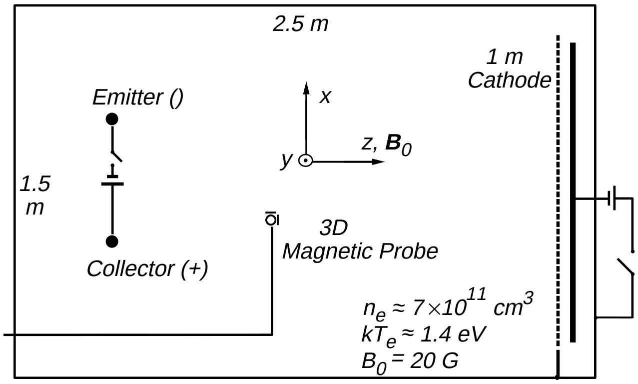

Figure 1. Schematic drawing of the experimental arrangement with basic diagnostics and parameters.

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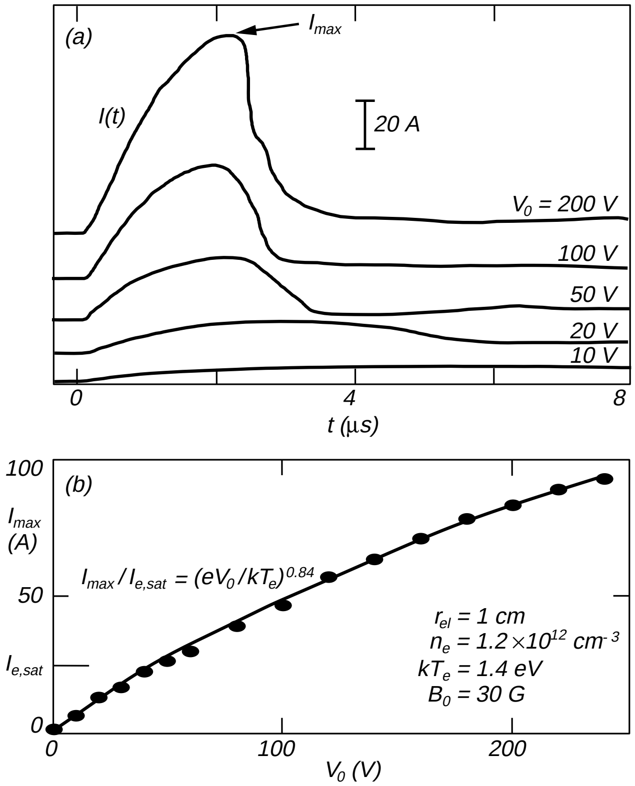

Figure 2. (a) Collected current at different dc voltages V_0 applied to a 2 cm diam disk electode. Peak current exhibits no saturation with voltage. Current collapse is due to density modification in the current flux tube. (b) Current-voltage characteristics follows a power law. Current collection in excess of the initial electron saturation current is possible to electron heating.

Current Collection and I-V Characteristics

We first discuss the current collection to a positively biased electrode. Figure 2a Fig. 2a shows the current waveform, $I(t)$, when a step function voltage, $V(t \leq 0) = 0$; $V(t > 0) = V_0$, is applied to a 2 cm diam disk electrode. The prominent feature is a current overshoot which develops as the applied voltage exceeds the plasma potential. Figure 2b Fig. 2b presents the variation of the peak overshoot current with voltage, $I_{\max}(V)$, which shows no saturation at the Langmuir limit, $I_{e,sat} = Ane\sqrt{kT_e/2\pi m_e} \simeq 23$ A based on the initial density and temperature ($n = 7 \times 10^{11}$ cm^{-3}, $kT_e = 1.4$ eV). The normalized I-V curve closely follows a power law, $I_{\max}/I_{e,sat} \simeq (eV/kT_e)^{0.84}$. The transient current is not caused by a displacement current associated with the sheath capacitance ($I \neq CdV/dt$), but it is a real electron conduction current. The current rise time is determined by the tether inductance, $dI/dt \simeq V_0/L_{tether}$. The overshoot phenomenon is caused by time-dependent and nonlinear effects neither of which are considered in steady-state theories applied traditionally to this problem [*Langmuir and Blodget*, 1924; *Parker and Murphy* ,1967; *Laframboise and Sonmor*, 1990]. The time dependence of the whistler electromagnetic fields provides, even without collisions, radial electron cross-field drifts into the flux tube of the collector. Thus, the current is not limited by the thermal electron flux but is driven by a propagating electric field extending far beyond the Debye sheath. When the current density in the flux tube approaches the Langmuir limit, electron heating arises. This prevents the drift velocity to exceed the thermal velocity, forbidden by strong instabilities [*Buneman*, 1959], yet allows the current to exceed the *unperturbed* electron saturation current. The large electric field *outside* the Debye sheath causes the unmagnetized ions to be radially expelled from the current channel. With $n_e \simeq n_i$, the density depletion causes the collapse of the large current. The duration of the current overshoot is approximately an ion transit across the current channel as confirmed by varying the ion mass and electrode size [*Stenzel and Urrutia*, 1997].

Direct observations of electric fields, dissipation and heating are shown in Fig. 3. Fig. 3 The electric field is predominantly radial except near the electrode where the current density is largest. The dissipation maximizes near the electrode (J_zE_z) but also arises on the sides of the current channel (J_rE_r). Dissipation causes electron heating which is unambiguously identified from the diamagnetic field in the current channel, $\Delta B_z \propto \Delta kT_e$. It is measured well after the end of a short current pulse when parallel heat transport

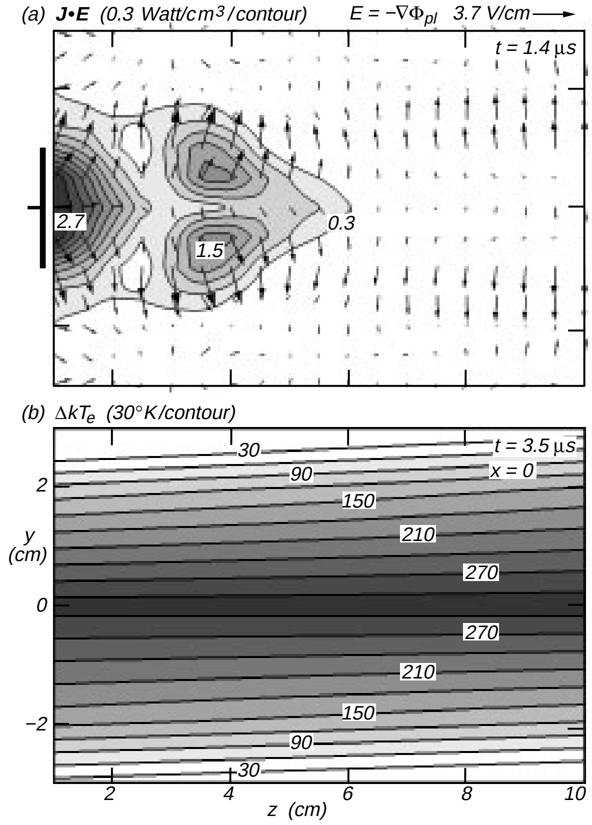

Figure 3. (a) Electric field and Joule dissipation near current maximum ($I_{\max} \simeq 20$ A). Dissipation peaks near the electrode where anomalous parallel electric fields are produced by electron drifts close to the thermal speed. (b) Electron heating observed *after* the end of a short current pulse (20 A, 0.2 μs). The temperature change is obtained from the diamagnetic field B_z opposing the uniform field $B_0 = 15$ G.

has created an axially uniform flux tube of heated electrons in pressure equilibrium, $B_z^2/2\mu_0 + nkT_e = \text{const.}$

The transient effects observed in the laboratory are thought to be relevant to a moving collector with a high dc potential such as TSS-1. Due to the satellite motion, the stationary plasma experiences time-varying fields, hence the collected current in each flux tube is a transient current. As in the laboratory, the transient I-V characteristics for TSS-1R exhibits no saturation. Currents in excess of the steady-state limit can be collected when the electrons are heated. Since in the laboratory electron heating is observed for collector voltages $eV_0/kT_e \geq 100$, even stronger heating should occur in space for collector potentials $eV_{TSS-1R}/kT_e \geq 5000$. However, density depletion in the flux tube and associated current loss may not play a significant role in space since the satellite velocity (≈ 7 km/s) well exceeds the sound speed (≈ 1 km/s).

Current Closure

In the laboratory experiment, a pulsed voltage is applied to stationary, tethered electrodes. The exciter structure acts like a dipole antenna for whistler waves. The propagating electromagnetic perturbation is supported by predominantly electron conduction currents. These are closed at all times since $\nabla \cdot \mathbf{J} \simeq \nabla \cdot (\nabla \times \mathbf{B}/\mu_0) = 0$. The cross-field current closure in a collisionless electron magnetohydrodynamics (EMHD) plasma is produced by electron Hall currents which dominate over Pedersen currents, polarization currents, and ion currents. No conducting boundaries are involved in the current closure. Contrary to MHD models, the self-consistent electric field in the plasma is not parallel to the tether but perpendicular to it and to $\mathbf{B}_0$. It is created by a space charge separation, i.e., an unclosed drift of electrons in the inductive electric field of the cross-field current and $\mathbf{B}_0$ [*Urrutia et al*, 1994]. The flux tubes of the two electrodes are also charged due to the collection/injection of electrons. The resulting radial electric field produces an azimuthal Hall current which, when added to the field-aligned current, gives rise to helical current density lines. Thus the current path consists of two field-aligned current spirals closed by a cross-field Hall current at the front of the current system which expands at the whistler wave speed along $\mathbf{B}_0$. The insulated tether plays as important a role as the conducting end electrodes in establishing a closed current circuit.

As explained above, the coherent wave structure of a moving dc tether is obtained by Huygen's principle of superimposing individual wavelets. Figure 4 Fig. 4 displays current density lines of such a "whistler wing." It is a dc structure in the moving frame but a transient wave phenomenon in the plasma rest frame. The current leaves each electrode in a multitude of right-handed spirals whose axes are inclined to $\mathbf{B}_0$ at an angle determined by the velocities of the spacecraft and the whistler wave, $\theta = \tan^{-1}(V_{sc}/V_{whistler})$. For purpose of demonstration, the wing angle in Fig. 4a Fig. 4a is chosen much larger than for conditions appropriate to TSS-1R ($\theta < 1°$). Figures 4b,c Fig. 4a,c show that the currents flowing along the wings are shunted by cross-field electron Hall currents. Since low frequency whistlers propagate within a ray cone of $\Delta\theta \simeq 20°$ [*Helliwell*, 1965] the current spreads rapidly with distance from the tether. The current channels from the satellite and the orbiter overlap at a distance $L \simeq l_{tether}/2\tan 20° \simeq 27$ km. Both current spread and shunting prevent the formation of a long "phantom loop" from the tether into the lower ionosphere as predicted by MHD theories.

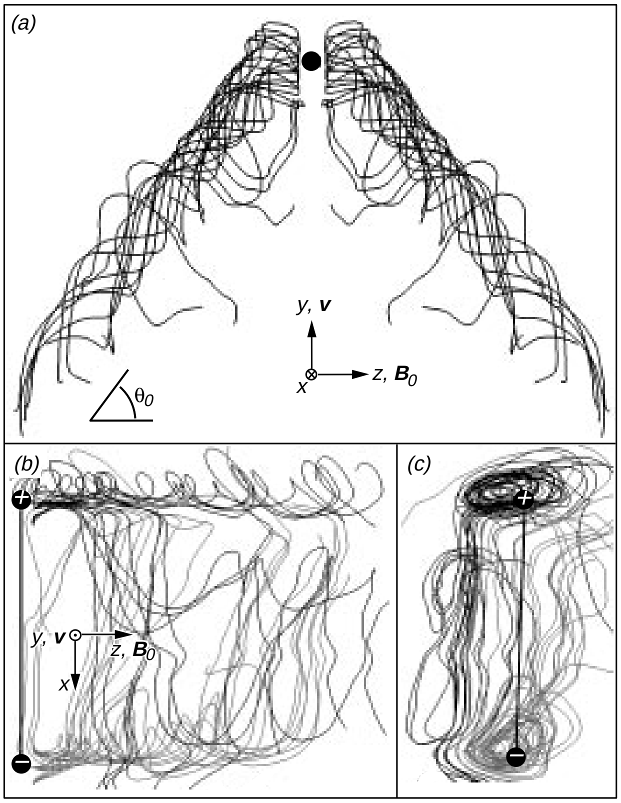

Figure 4. Current density lines in a "whistler wing" of a moving electrodynamic tether. The wing is a coherent dc structure in the moving frame but a transient wave phenomenon in the plasma rest frame. It has been constructed, following Huygen's principle of superposition of wavelets, from measured whistler pulses of the laboratory experiment. The wing angle for TSS1 would be much smaller than shown here. (a) Side view showing the wing inclination with respect to $\mathbf{B}_0$ (left wing measured, right wing mirrored). (b) View of left wing along the spacecraft velocity vector. The two current channels of the electrodes are closed by cross-field electron Hall currents. Dark current density lines originate near the collector, light lines near the electron emitter. (c) View down the wing showing current helicity in the oblique current channels of the electrodes.

Conclusions

Laboratory observations suggest that tether currents are transient EMHD currents which can be collected and closed by Hall currents across the ambient magnetic field. Electron heating allows current collection in excess of the ambient saturation current. The current closure occurs in a relatively short whistler wing.

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