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MODELING OF INDUCED CURRENTS FROM ELECTRODYNAMIC TETHERS IN A LABORATORY PLASMA

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Abstract. The presently accepted picture of the current path for electrodynamic tethers envisions a quasi-dc current flow in a "phantom loop" consisting of the tether, two field-aligned current channels into the ionosphere and a cross-field closing current in the E-layer. Predictions are made on the establishment and maintenance of a current loop in space based on observations of time-dependent currents between tethered electrodes in a large laboratory magnetoplasma. In addition to radiation from the contactors ("whistler wings"), the insulated tether is observed to emit waves (a "whistler wedge"). The "wedge" provides closure during loop formation by carrying cross-field polarization currents. Whistler spread within the ray cone leads to overlapping of the current wings not far from the tether hence minimizing the role of the ionospheric closure. Maintenance of the loop requires the continuous emission of whistler waves by the entire tether thereby providing severe radiation losses.

Introduction

One of the most interesting aspects of the electrodynamics of tethers in space [Penzo and Ammann, 1989] is the current path and cross-field closure in a collisionless magnetoplasma. In the absence of experimental data, the following theoretical picture has found acceptance [Banks et al., 1981]: The charge clouds created by the contactors generate essentially field-aligned currents extending into the ionospheric E-region where they are shorted by Pedersen currents. This dc current model does not examine the time-dependent inductive processes which create and maintain the loop. In this Letter, the evolution of the tether current system is deduced from laboratory observations (space and time) of currents collected by tethered electrodes in a large collisionless plasma. The convective derivative (moving tether with dc current) is modeled by the time derivative, $\mathbf{v}\cdot\nabla \rightarrow \partial/\partial t$ (stationary tether with pulsed current). The major new findings are cross-field polarization currents associated with waves emitted by the insulated tether at turn-on and turn-off. Such currents, together with the contactors' currents [Urrutia and Stenzel, 1989], form propagating, self-closed current loops in the laboratory. In space, the motion of the tether leads to continuous emission of such loops. Hence, radiation losses should be much greater than the levels previously envisioned [Barnett and Olbert, 1986; Hastings et al., 1988]. Superposition of these loops may indeed lead to the creation of a quasi-dc current loop. However, whistler wave spread within the well known ray cone ($\theta \leq 19°$, Helliwell, 1965; Barnett and Olbert, 1986) effectively terminates the loop not far from the tether system. The possible use of the loop as an ELF antenna [Banks et al., 1981] is therefore in doubt.

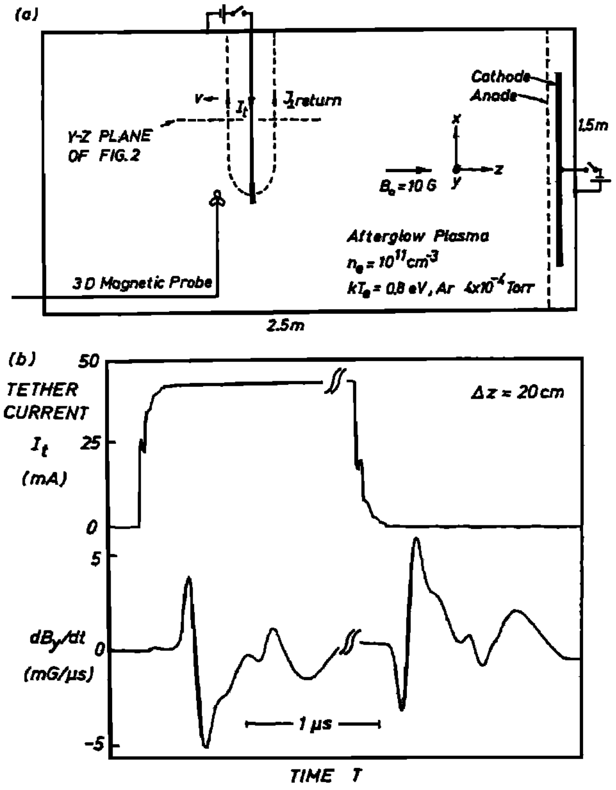

Fig. 1 a) Schematic drawing of the plasma device and the pulsed current system. The perturbed field, $\mathbf{B}(\mathbf{r},t)$ ($\ll \mathbf{B}_o$), is measured with magnetic probes from which the current density, $\mathbf{J} = \nabla \times \mathbf{B}/\mu_o$, is calculated. Cross-field tether currents (I_t, vertical wire) are observed to induce return currents (dashed lines) which provide current closure while the current front propagates at whistler wave speeds v along $\mathbf{B}_o$. b) Tether current, I_t and $\partial B_y/\partial t$ ($\partial B_\theta/\partial t$ in the wire's cylindrical coordinates) at (20,0,-20) vs. time. Note that the response at turn-off differs from turn-on only by its sign.

Experimental Arrangement

The experiment (Figure 1a) is performed in a large (1 m diameter. × 2 m length) Maxwellian afterglow plasma ($n_e \approx 10^{11}$ cm^{-3}, $kT_e \approx 1$ eV, $n/(dn/dt) \approx 1$ ms) immersed in a uniform axial dc magnetic field ($\mathbf{B}_o \approx 10$ G). A plane, one-sided disk electrode (5 cm diameter) is inserted into the middle of the plasma via an insulated radial wire (tether) of approximately 1 m in length. The local current density (conduction + displacement) is obtained via Ampere's law, $\mu_o\mathbf{J} = \nabla \times \mathbf{B}$, from time and space resolved probe measurements of the perturbed magnetic field, $\mathbf{B}(x,y,z,t)$, over a field-aligned plane perpen-

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dicular to the tether. The plane is at approximately 20 cm from the tether end contact. Plasma parameters are obtained from Langmuir probe traces. The small electron current drawn from the electrode ($I_c \approx 50$ mA $\ll I_{e,sat} \approx 20$ A, $\Delta t \approx 3$ μs, $t_{rise} \leq 100$ ns) does not cause nonlinear modifications of the plasma [Urrutia and Stenzel, 1986]. The ions are effectively unmagnetized (electrode size $< r_{ci}$, $\Delta t < 1/\omega_{ci}$), which also holds for initial tether experiments in space.

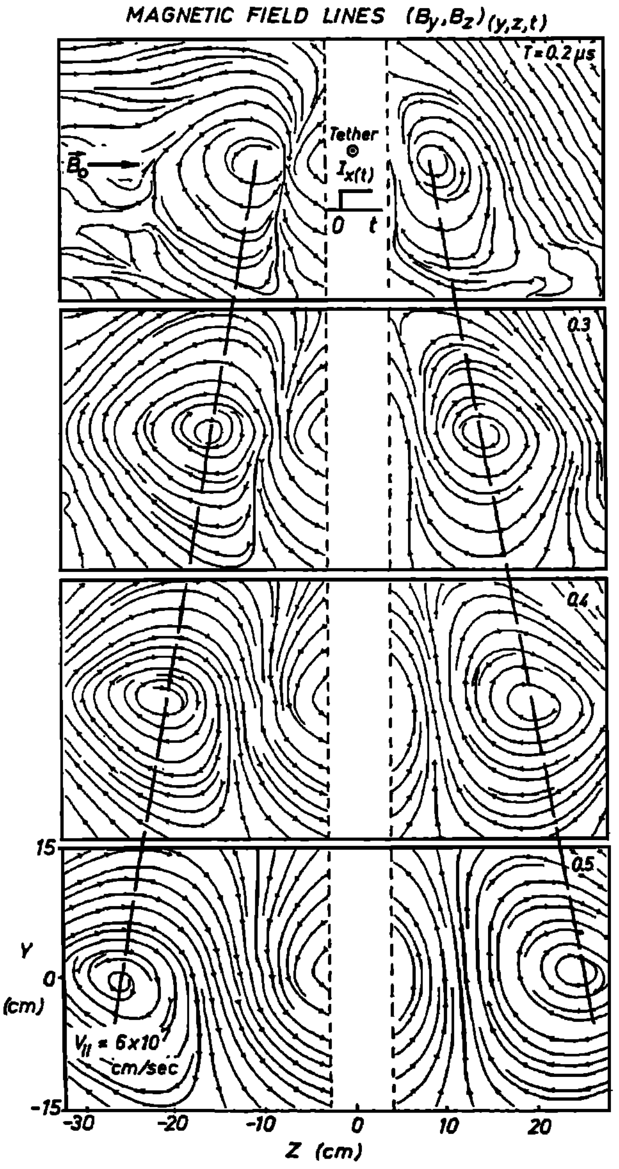

Fig. 2 Magnetic field lines of the field perturbation created by a current step ($I_x = 50$ mA) in an insulated, stationary tether wire aligned $\perp \mathbf{B}_o$. The induced field is that of two image line currents, antiparallel to the tether current, but propagating away along $\mathbf{B}_o$ at whistler wave speeds. No data was taken between the dashed lines due to overlapping of magnetic probe and tether/electrode.

Waves and Currents from the Tether

The response of a plasma to the switch-on/switch-off of a magnetic field obeys Lenz's law: an opposing/sustaining field is induced in the plasma. This is illustrated in Figure 1b where the evolution of $\partial B_y/\partial t$ at (20,0,-20) and I_{tether} versus time are shown. The time rate of change is displayed instead of B_y because the oscillatory nature of the plasma is thus more readily observed. It is noted from this display that the response at turn-on and turn-off differ only by the sign. Hence, any current system induced at turn-on is reversed in direction at turn-off. A moving magnetic field structure is revealed when similar observations are made over a y-z plane (see Figure 1a). Figure 2 displays magnetic field lines projected in such a plane. No data is taken in a vertical strip immediately adjacent to the tether since the magnetic probe and the tether wire physically interfere. For different times t after the switch-on of the current step, two magnetic "islands" propagating away from the tether wire are observed. The perturbation moves along the ambient field $\mathbf{B}_o$ ($\gg \mathbf{B}_{wave}$) at approximately the group velocity of a whistler wave packet [Helliwell, 1965] given by $v_g = \partial\omega/\partial k \approx 2c(1 - \omega/\omega_c)^{3/2}(\omega\omega_c/\omega_p^2)^{1/2} \approx 600$ km/s for $f_{pe} \approx 6$ GHz, $f_{ce} \approx 56$ MHz, $f \approx 1/t_{rise} \approx 20$ MHz. Earlier investigations with a repetitive current waveform have confirmed that both dispersion and polarization of the excited waves is that of whistlers [Urrutia and Stenzel, 1989]. The wave packet exhibits helicity, i.e., there are (B_x-B_y) loops linked through the loops of (B_y, B_z).

Subtraction of the free-space magnetic field associated with the wire current ($B = \mu_o I_{tether}/2\pi r$) from the total field in the plasma indicates that as much magnetic energy is associated with the plasma response (the wave/polarization current) as with the stored free-space energy ($B^2_{free\text{-}space}/2\mu_o \approx B^2_{wave}/2\mu_o$. The same result, of course, holds during turn-off. However, the energy source for the plasma response is then the stored energy in the free-space field surrounding the tether. Thus, 50% of the total energy spent by the tether to establish magnetic fields is radiated away via waves.

The current density $\mathbf{J} = \nabla \times \mathbf{B}/\mu_o$ is seen to have a component J_x associated with the magnetic islands. The induced current is directed opposite to the tether current as deduced from Figures 1b and 2, and flows perpendicularly to the static magnetic field $\mathbf{B}_o$. A contour plot of $J_x(y,z)$ is shown in Figure 3a while Figure 3b presents the integrated cross-field current, $I_x = \iint_S J_x\, dydz$, flowing through two surface area S (20 × 20 cm^2). As the propagating wave polarization current passes through the fixed area A, it equals the tether current to within measurement accuracy (±20%), i.e., the total induced current of both right and left propagating waves form a complete cross-field current closure for the tether current. This is consistent with the fact that the field-aligned current from the electrode has not reached the chamber wall, hence cannot provide the current closure. While the tether current has become time independent ($\partial/\partial t \approx 0$) the plasma current is propagating, i.e., locally time-dependent. In addition to the "primary" current system, a secondary induced current system (dashed contours, Figure 3a) is set up in the plasma to oppose it. This is consistent with the wave nature of the current. As discussed above (see Figure 1b), the induced cross-field currents reverse sign when the tether current is switched off.

Model of Induced Currents for Tethers in Space

The induced currents are produced in the laboratory plasma by time varying currents in a stationary frame. In space, a moving, insulated tether with dc currents will also induce

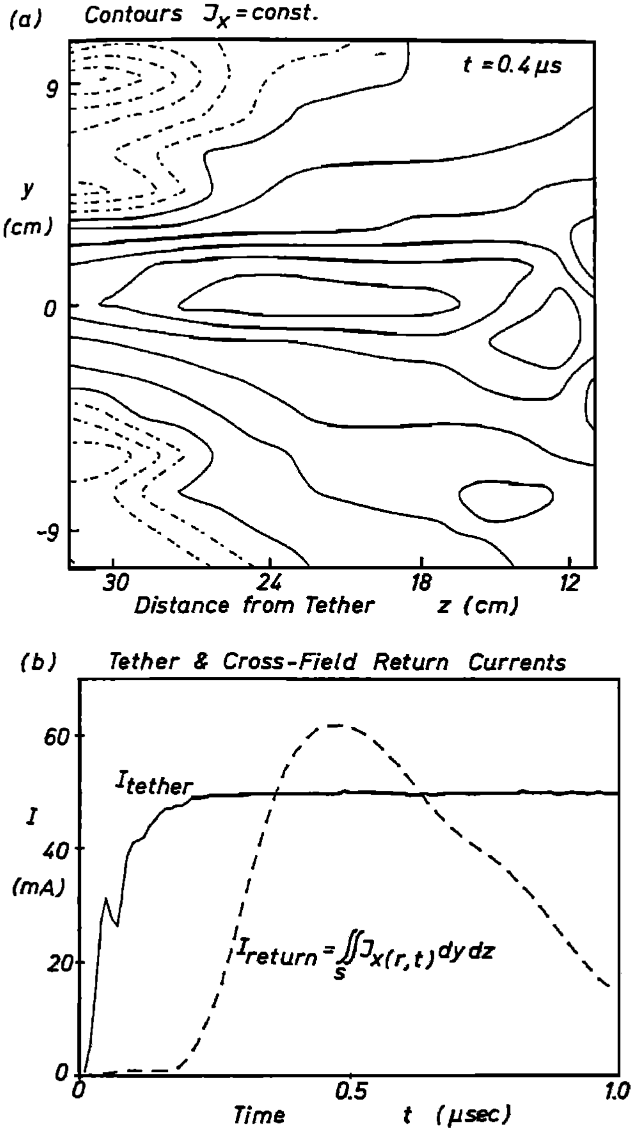

Fig. 3 Data showing current closure by induced cross-field polarization currents. (a) Contours of constant current density $J_x(y,z)$ (solid contours, J_x into paper, 0.04 mA/cm^2/contour) in the region of the left induced magnetic island (see Fig. 2). "Secondary" induced currents (dashed contours, J_x out of paper) have been enhanced (0.01 mA/cm^2/contour). (b) Time dependence of the tether current and the induced cross-field return current (dashed curve) obtained by integrating J_x for both magnetic islands over y-z planes as in (a). The time dependence $I(t)_{return}$ is caused by the propagation of the wave across the fixed surface S. The peak return current accounts for the tether current to within measurement accuracy ($\approx$ 20%).

time-varying currents in a stationary space plasma because of Faraday's law together with the convective derivative ($d/dt = \mathbf{v}\cdot\nabla$). The response of the plasma to a rapidly moving non-uniform magnetic field surrounding the tether wire is qualitatively analogous to that of a magnetic pulse, i.e., a wave packet will be launched on each field line [Dobrowolny and Veltri, 1986]. While this well-known picture led to the prediction of Alfvén and possible whistler wings radiated from the electrodes/contactors (Drell et al., 1965; Hastings et al., 1988), it does not seem to have been considered for the tether itself. The laboratory observations clearly show the efficient excitation of a whistler wave from a long wire across $\mathbf{B}_o$. Thus,

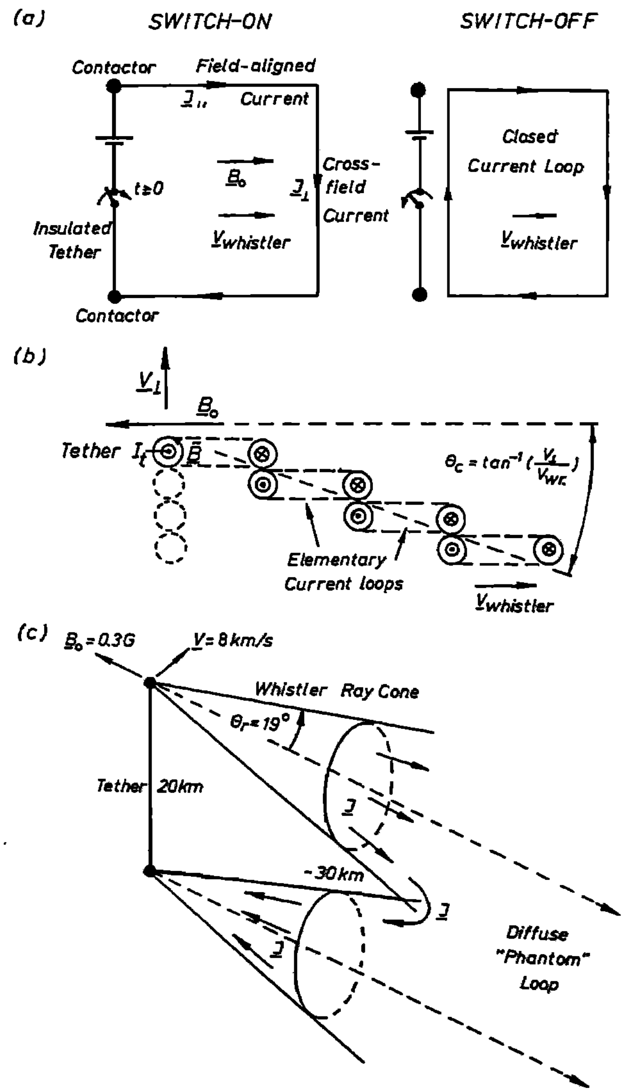

Fig. 4 Schematic drawing of proposed current closure for electrodynamic tethers in space. a) Summary of the laboratory observations. At turn-on, a cross-field polarization $\mathbf{J}_{\perp}$ is induced in the plasma. This current, together with the currents to the contact ends, forms a current loop. Because the currents couple to whistler waves, they propagate along $\mathbf{B}_o$. At turn-off, a plasma current is induced that attempts to maintain the tether's dc magnetic field. This current forms a closed loop with the already propagating currents. The loop then travels and spreads along $\mathbf{B}_o$. b) In space, a tether system moving with velocity $\mathbf{v}_{\perp}$ across $\mathbf{B}_o$ excites a stream of closed current loops due to its short transit time through each flux tube. The superposition of these loops leads to a quasi-dc "phantom" loop inclined at a negligibly small angle $\theta_c = \tan^{-1}(v_{\perp}/v_{whistler}) \approx 0.2°$ with respect to $\mathbf{B}_o$. c) Because the current is carried by diverging whistler waves, the loop effectively closes when the ray cones from each contactor begin to overlap, i.e., at $r \approx L/(2\tan 19°) \approx 30$ km away from the tether (where L is the tether length and 19° is the ray cone angle for $\omega \ll \omega_c$).

one can expect that a tether in space will generate a wedge-like whistler wave along its entire length (≈ 20 km) due to the wave spread within the ray cone. The waves emitted by the tether depend mainly on the time rate of change of the tether magnetic field and its velocity and not on the length of the tether. The consequence of this whistler wedge is that it provides for a cross-field current closure and energy losses due to radiation of whistlers which have not been considered before.

Figure 4 displays schematic pictures of the proposed current system involving induced plasma currents. Figure 4a summarizes the laboratory observation after closing a switch at $t = 0$. The contactors emit whistler waves confined to ray cones, the tether emits a whistler wave confined to a wedge. The tether current is closed by two field-aligned, spreading current channels and a propagating, cross-field polarization current at the front of the whistler wave. Opening the switch at $t \approx \Delta T$ induces a cross-field current that closes with the currents already in place in the plasma. The closed current loop then moves along the field lines spreading within the ray cone as it propagates. Analogously, elementary loops are created and shed by the tether at every field line it crosses (Figure 4b). Superposition of the multitude of loops does lead to the formation of a quasi-dc loop with a diffuse cross-field current system. However, a clearly identifiable loop does not extend to the ionosphere because ray cones of angle of angle $\theta_c \approx 19^\circ$ ($\omega \ll \omega_c$) emitted by the contactors of a 20 km long tether begin to overlap at a distance of $r \approx 10$ km/*tan* 19° ≈ 30 km (Figure 4c). Beyond this scale length, distinct current channels can no longer be identified. It is also possible that ducting of whistlers on different field lines further complicates the current channel. While the current in such a loop may be modulated (e.g., by modifying the current strength), coupling to ELF waves as previously envisioned [Banks et al., 1981; Penzo and Amman, 1989] may be inefficient in view of the poor definition of the current path beyond the scale length of overlapping ray cones.

It has been previously assumed that wave emission is mostly due to the contact ends [Barnett and Olbert, 1986]. Such prediction is based on the assumption that the tether-plasma current system reaches a steady state. Our experimental observations indicate that the current in the frame of the plasma is *never* in steady state. Current loops are constantly created. Consequently, a significant part of the electrical energy of the tether is continuously being converted to wave energy which is subsequently deposited in the plasma and lost to the tether system.

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