WHISTLER WINGS FROM MOVING ELECTRODES IN A MAGNETIZED LABORATORY PLASMA

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Abstract. In a large laboratory plasma the current pattern set up by moving electrodes has been measured. It is observed that the current flows oblique to the magnetic field $B_0$ at an angle given by the electrode speed across $B_0$ and the current penetration along $B_0$ which is controlled by whistler waves. The current pattern, characterized as "whistler wings", occurs irrespective of whether the electrodes collect electrons/ions or emit fast electron beams. These results are relevant to active experiments in space involving electrodynamic tethers, beam injections and large space stations.

Introduction

Wave emission from moving sources in plasmas is a topic of fundamental interest [Papas, 1965] and of great importance to the interaction of moving conductors with magnetized space plasmas [Drell et al., 1965]. A particular example of current interest is the electrodynamic tether, i.e. two electrodes connected by a long wire whose motion $v$ across the magnetic field $B_0$ gives rise to a dc potential difference $V = \int v \times B_0 \cdot dz$ [Banks et al., 1981; Dobrowolny, 1978]. It is thought that a dc current flow can be established between the two electrodes by field-aligned currents through the magnetized plasma and cross-field current closure in the collisional ionosphere. However, due to the motion of the electrodes relative to the ambient plasma the current flow will be oblique to the magnetic field with an angle determined by both the electrode velocity across $B_0$ and the velocity of current propagation along $B_0$. The latter is usually believed to be the Alfvén speed and, ever since the original theory by Drell et al., [1965], it is thought that the current leaves the electrodes along "Alfvén wings." Recent calculations of the radiated wave power have been extended to the frequency regime of whistlers and lower hybrid waves [Barnett and Olbert, 1986; Hastings et al., 1988]. Since the concept of wings has not yet been tested in space we have modeled some of its aspects in a laboratory experiment [Stenzel and Urrutia, 1986; Urrutia and Stenzel, 1989]. The present Letter describes first observations of the current flow from moving electrodes which we would like to describe as "whistler wings." The relevance of these observations to electrodes in space will be discussed.

Experimental Arrangement

The experiment (Figure 1) is performed in a large (1 m diam. x 2 m length) Maxwellian afterglow plasma ($n \leq 10^{12}$ cm$^{-3}$, $kT_e = 10$ kT $\leq 3$ eV) immersed in a uniform dc magnetic field ($B_0 = 20$ G). Movable electrodes are inserted into the plasma and biased so as to establish a current flow through the plasma. The local current density may be obtained via Ampere's law $J = \nabla \times H$ from time and space resolved measurements of the perturbed magnetic field $B(r,t) = \mu H$. Plasma parameters are derived from Langmuir probe traces.

In the present experiment the current density $J = nev$ is kept small, $v \ll (kT_e/m_e)^{1/2}$, so as to avoid nonlinear modifications of the background plasma [Urrutia and Stenzel, 1986]. The pulsed discharge plasma ($t_{rep} = 1$ sec) is highly reproducible ($\Delta n/n < 5\%$) so as to allow data collection and synthesis from repeated experiments. For the duration of the measurement of the current flow ($\Delta t \leq 10$ msec) the plasma decay ($\tau = 1$ msec) can be neglected. The current flow has been established either between two electrodes floating with respect to the chamber wall (100V, 1A, 1 cm diam. electron beam and a 1 cm$^2$ plane electron return-current collector, separated 15 cm across $B_0$, both moving simultaneously across $B_0$), or between a single moving electrode (2.5 cm diam. sphere) and the distant chamber wall. The observed wings are not subject to boundary effects or collisions with neutrals. The ions are effectively unmagnetized (electrode size $<r_{ci}$, transit time through flux tube $<\omega_{ci}^{-1}$). These conditions are characteristic of many active experiments in space.

![Fig. 1 Schematic arrangement of the laboratory experiment.](image)
Modeling Electrode Motions

Since it is essentially impossible to move an electrode at the speed of a whistler wave ($v > 100 \text{ km/sec}$, $V_\text{whistler}^2/2 > 10^4 J$) or very difficult to produce correspondingly fast plasma flows we have taken a different, yet very simple, approach, i.e., linear superposition of electromagnetic fields. As shown in Figure 2a the continuous motion of the electrode is broken up into individual adjacent steps ($\Delta x =$ size of electrode) and the dc current is divided into a corresponding sequence of current pulses ($\Delta t = \Delta x/v =$ transit time of electrode through its diameter). At each position of the pulsed electrode the magnetic field perturbations are measured and stored digitally. When superimposing all the retarded field contributions we ascertain (and prove below) that we obtain approximately the field of an electrode moving at a constant velocity $v$ and drawing a dc current $I$.

From previous investigations [Urrutia and Stenzel, 1989] we know that switched currents from a stationary electrode propagate along $B_0$ with the speed of a whistler wave packet (frequency $\approx$ inverse pulse width). Hence, as schematically shown in Figure 2b, an electrode moving at a velocity $V_\text{whistler}$ ($I B_0$) will set up an oblique current trail of wing in the $v-B_0$ plane at an angle $\theta (\approx J,B_0)$ given by $\tan \theta = V_\text{whistler}/V_X$. In order to map this structure we have measured at each probe position $(x,z)$ the fields for each electrode position ($x_i, t = 1, \ldots, 10$) versus time. Due to the extensive data sets and limited space we restrict ourselves to the display of one field component, $B_z$, which maximizes in the current channel (we recall that Urrutia and Stenzel [1986] have shown that the current flow is helical as in a flux rope and $B_z$ is associated with $E \times B_0$ electron drifts).

The validity of linear superposition of fields in the present experiment has been established as shown in Figure 2c. Using two separate electrodes at different positions the fields $\vec{B}$ due to current pulses applied individually and jointly have been recorded at various spatial locations. Within measurement accuracy ($\pm 10^{-4}$ G), no difference was found between the fields from joint pulses or the linear superposition from individual pulses.

Finally, the concept of approximating a dc current by a sequence of current pulses has been tested. For a single electrode at a fixed position, Figure 2d shows (1) the linear superposition of fields due to $N = 20$ delayed pulses and (11) the field due to a single long pulse (quasi-dc current) which is approximately equivalent to the superposition of short pulses. Except for small deviations at turn-on and turn-off, the superposition of short current pulses yields the same field as that generated by the quasi-dc current. With these tests we are confident that the present approach is scientifically sound.

Observations of Wings

Figure 3 shows typical contour plots of the perturbed magnetic field $B_z(x,z)$ at different times for the spherical electrode moving at a constant velocity. In Figure 2a we see the principle of current wing generation by moving electrodes and supporting observations. (a) The continuous motion and current are broken up into increments, the effects of which are measured separately and later superimposed. (b) A magnetic wave/current wings arise from the electrode motion across $B_0$ and the signal propagation along $B_0$. (c) Experimental verification of linear superposition of fields and (d) of approximating dc currents by summation of delayed pulses (see text).
constant speed \(v_x = \Delta x / \Delta t = 2 \times 10^7 \text{ cm/sec}\) and drawing a constant electron current \(I = 1 \text{ A}\). The contours of constant wave amplitude are inclined at an angle \(\theta = 40^\circ = \tan^{-1}(v_x/v_z)\) where \(v_z = 3 \times 10^7 \text{ cm/sec}\) is the observed propagation speed of current pulses along \(B_0\). With increasing time the wave wing moves with the electrode in the \(x\) direction, i.e. the wings are stationary in the moving frame as long as the plasma parameters are constant. Although not displayed, wave wings also exist for the other field components, hence for the current density \(J\). The decay of the field/current density with distance \(z\) indicates a broadening of the current channel in \(x\) and \(y\) due to the oblique propagation characteristics of whistlers [Helliwell, 1965]. Note that the observed wings extend into the far zone \((z > \lambda) \approx 9 \text{ cm}\) of whistlers with characteristic frequency \(\omega/2\pi = v_y/d = 6 \text{ MHz}\).

Figure 4 shows the wings of a moving electron beam source (100 eV, 1A, 0.8 cm diam.). The return current is collected by a co-moving electrode spaced 15 cm across \(B_0\) from the emitter. The electrode system is electrically floating with respect to the chamber wall, hence models qualitatively a tethered satellite/beam current system in space. It is most remarkable that the electron emitter also generates a whistler wing rather than a current flow determined by the beam particles. The propagation speed of the beam electrons along \(B_0\) is much larger \((v_b = 6 \times 10^7 \text{ cm/sec})\) than that of the current \((v_z = 3 \times 10^7 \text{ cm/sec})\) or of the electrode \((v_x = 2 \times 10^7 \text{ cm/sec})\) such that the beam remains nearly field aligned \((\theta_b = 2^\circ)\) while the current is oblique \((\theta_c = 18^\circ)\). We have verified the presence and speed of the beam particles by optical diagnostics. The energetic beam electrons excite transitions in ions and neutrals which are readily observable in the dark background plasma. The insert of Figure 4 shows time and space resolved light measurements from a fast photomultiplier tube for a 50 nsec, 100V, 1A electron beam pulse. Such time-of-flight measurements yield directly the particle speed \(v_p = \Delta z / \Delta t = 50 \text{ cm/50 nsec} = 6 \times 10^6 \text{ cm/sec}\) which confirms that the beam has long penetrated before the current arrives. The beam must be current-neutralized by the background electrons since no net magnetic field is generated.

**Discussion**

The present laboratory observations confirm the existence of wave/current wings emitted from a moving electrode with a constant current. However, since both in the laboratory and in most satellite applications the ion Larmor radius is larger than the electrode size and the electrode velocity higher than the ion thermal speed, the spectrum of waves excited falls into the electron whistler wave branch rather than into the Alfvén branch \((\omega > \omega_{ci})\). For example, for a 1 m diameter electrode the excitation frequency based on the transit time is \(f = 8 \text{ kHz}\) which excites whistlers rather than Alfvén waves \((\omega_{ce} = 1 \text{ MHz}, \omega_{ci} = 30 \text{ Hz} @ B = 0.3 \text{ G}, 0^\circ)\).

Since the group velocity of whistlers is much higher than the spacecraft velocity \((v_g = 2c (\omega_{ce}/\omega p_e)_{1/2} = 20,000 \text{ km/sec})\) the wing angle \(\theta\) is negligibly small. However, the current will not be confined to a narrow flux tube because whistler waves diverge from a small source and radiate into a ray cone of angle \(\theta > 1^\circ\) [Helliwell, 1965]. Thus, the current "wings" of two electrodes separated by 20 km across \(B_0\) will overlap at a distance of <50 km along \(B_0\) so that current "closure" takes place well above the E-layer.

The laboratory observations of the current...
flow by a moving electron beam also has interesting implications for active experiments in space. Since the current is not carried by the beam particles but by whistler wings, a modulated beam is not equivalent to a long wire antenna with respect to exciting VLF waves. The magnetic signal diverges across $B_0$ as rapidly as for a plain electron-collecting electrode.

Further, our observation of wings are important features for spacecraft in the solar wind since the high streaming velocity and typical satellite scale length couples to whistlers rather than to Alfvén waves.

Finally, our observations show that whistler wave emission ($k = k_1$) contributes greatly to the current system impedance. This is in contrast to the work of Hastings et al. [1988], where attention is mostly given to lower hybrid waves ($k = k_2$).

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References

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