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Laboratory Experiments on Current Flow Between Stationary and Moving Electrodes in Magnetoplasmas

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Laboratory experiments have been performed in order to investigate the basic physics of current flow between tethered electrodes in magnetoplasmas. The present extended abstract summarizes the major findings and points to references for further details. The experiments are performed in an effectively very large laboratory plasma (2 km $\perp \vec{B}$, 5 km $\parallel \vec{B}$ when scaled in terms of Debye lengths to low Earth orbit conditions) in which not only the nonlinear current collection is addressed but also the propagation and spread of currents, the formation of current wings by moving electrodes, the current closure, and radiation from transmission lines are explored.

The laboratory plasma[1] consists of a pulsed dc discharge (1m $\perp \vec{B}$, 2.5m $\parallel \vec{B}_o$, $n_e \lesssim 10^{12}$ cm^{-3}, $kT_e \lesssim 5$ eV, $B_o \lesssim 100$ G, Ar 3×10^{-4} Torr) whose Maxwellian afterglow provides a quiescent, current-free uniform background plasma. Electrodes consisting of collectors ($\simeq$ 1 cm diam) and electron emitters ($\simeq$ 1 cm diam. hot cathode) are inserted into the plasma and a pulsed voltage is applied between two floating electrodes via insulated transmission lines. Besides the applied current in the wire the total current density in the plasma is obtained from space and time resolved magnetic probe measurements via Maxwell's law, $\nabla \times \vec{H} = \vec{J} + \partial\vec{D}/\partial t = \vec{J}_{tot}$. Langmuir probes yield the plasma parameters n_e, kT_e, and ϕ_{plasma}.

Although current collection on a spacecraft appears to be a dc problem the rapid motion across the magnetic field results in a pulse-like current flow in the stationary plasma. When such pulses are applied to fixed electrodes in the laboratory plasma the current front is found to penetrate as a whistler wave packet along $\vec{B}_o$.[2] Whistlers rather than Alfvén waves are excited since the time variation (pulse width or electrode transit time across $\vec{B}_o$) are fast compared with the ion cyclotron period. When a sequence of pulses is applied and the electrodes are moved across $\vec{B}_o$ the situation of a moving tethered electrode system is modeled.[3] Superposition of wave packets from repeated measurements indicates the formation of a "whistler wing," i.e. an oblique current trail at an angle with respect to $\vec{B}_o$ determined by both the wave speed ($\|\vec{B}_o$) and the electrode speed ($\perp\vec{B}_o$). The current wings spread since the radiation sources (electrodes) are finite and the waves can propagate within a ray cone ($\theta_c \simeq 19^o$). Most interesting is the fact that the current wings do not depend on the collected/emitted particle speeds, i.e. whistler wings are observed for ion collection, electron collection and fast electron beam emission. Pulsed beams are current and charge neutralized by background electrons.[4] Current closure appears to arise from cross-field wave currents rather than collisional cross-field particle currents (Pedersen currents) or equivalent boundary currents (line tying).

Time-varying currents in stationary transmission lines (or dc currents in moving lines) are observed to induce plasma return currents.[5] These may couple to collective modes (whistlers) or diffuse resistively (eddy currents) depending on the direction (and motion) of the line with respect to the magnetic field $\vec{B}_o$. For the standard tether configuration ($\vec{v} \perp \vec{B} \perp \vec{\ell}$) the entire insulated wire can be expected to radiate a sheet-like whistler wing, not only the conducting end electrodes. Thus, the radiation resistance of the tether system is considerably larger than that of the electrodes alone.

Since it is desirable to conduct the largest possible current through the ambient plasma the question of plasma nonlinearities arises. The laboratory experiments have demonstrated the existence of a disruptive instability[6] which has also been conjectured theoretically.[7] When electrons are extracted from a flux tube in a magnetoplasma its potential rises leading to an acceleration of ions out of the flux tube. The resultant density depression reduces the collected current. At large current densities, the ion dynamics leads to a fluctuating current ($\partial I/I \sim 100\%$) as plasma periodically sloshes back and forth out of the flux tube near the positive electrode. When sufficient neutral gas is supplied ionization takes place near the anode which quenches the ion expulsion, hence current fluctuation. Such contactors formed by self-ionization of excess neutrals appear to occur in space as well.

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