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A new method for removing the blackout problem on reentry vehicles

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Supersonic vehicles are surrounded by a plasma layer which produces a cutoff layer for electromagnetic waves. Methods to remove the layer by gas releases, dc magnetic fields, and $\mathbf{E} \times \mathbf{B}$ flows have been proposed earlier. The present work suggests a new approach which is based on laboratory observations. Ions are expelled by a *time varying* magnetic field which creates a Hall electric field. The ion expulsion opens up a window of transparency for wave communications. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4795148]

I. INTRODUCTION

When a supersonic vehicle passes through the atmosphere it is surrounded by a plasma layer. Electromagnetic signals below the plasma frequency are highly attenuated causing a communication blackout. Remedial of the blackout has been a topic of intense research. It applies to spacecraft entering an atmosphere such as the reentry of the space shuttle, hypersonic vehicles like the scramjet or the Mars Pathfinder.[1]

Many different methods for removing the plasma layer have been proposed[2–4] and supported by theory,[5–9] computer simulations,[10,11] and laboratory experiments.[12–14] The plasma can be quenched by gas releases (H_2O, SF_6), static magnetic fields allowing propagation of whistler modes,[15] electron acoustic modes occurring in non-Maxwellian plasmas[16] or nonlinear waves[17] and $\mathbf{E} \times \mathbf{B}$ flows created by discharges on the surface of the vehicle have been proposed and partly tested in laboratory plasmas.[14]

The present paper describes a simpler method to remove the blackout layer, which is based on a laboratory observation. A rising magnetic field is generated by a pulsed current through an insulated conductor immersed into a plasma. The field magnetizes the electrons but not the ions. The magnetized electrons are expelled across the field, create a Hall electric field which subsequently expels the ions. A density depletion is created. With a suitable arrangement the plasma layer near the vehicle surface can be depleted such that a window for communication is opened. Since the depletion occurs only during the time-varying magnetic field the mitigation has to be repeated periodically during the blackout phase. The power requirement and weight of the mitigation scheme are modest. No dc magnet, rf discharge, or dc discharge with a hot cathode is needed as proposed earlier.[11,14]

The paper is organized as follows. The laboratory setup is presented in Sec. I, followed by the Experimental Observations in Sec. II. A proposal for an arrangement on a space vehicle is suggested in Sec. III, followed by a Conclusion in Sec. IV.

II. EXPERIMENTAL SETUP

The experiments are performed in a large discharge device designed to study phenomena in electron magneto hydrodynamics (EMHD) [Figs. 1(a)–1(e)]. A pulsed dc discharge is created with a 1 m diam oxide-coated cathode in Argon at a pressure $p \simeq 5 \times 10^{-4}$ Torr. A weak uniform magnetic field $B_0 = 5$G is applied axially to minimize the radial expansion of the column. The electrons are magnetized, the ions are not, which are the characteristics of EMHD plasmas.

An insulated wire is passed transverse through the plasma column. The line current is closed via a semicircular loop at the bottom of the chamber. The current flows through four turns of 1.5 mm diam Cu to enhance the magnetic field for given a current. When the current rises it produces an opposing inductive electric field along the wire. The magnetized electrons perform a radial $\mathbf{E} \times \mathbf{B}$ drift, the ions do not. This creates a radial space charge electric field which begins to accelerate the ions radially outward. The ion outflow is slightly faster than the ion sound speed. It continues as long as the wire current rises.

The plasma density is measured with a Langmuir probe which can be scanned in 3D radially and axially. The density is proportional to the electron saturation current which is measured. The discharge is pulsed and repeated with $t_{rep} \simeq 1$ s.

The pulsed wire current is generated by a simple capacitor discharge shown in Fig. 2. A 100 μF capacitor is charged with a dc supply (500 V, 30 mA) and discharged through a transistor switch into the wire loop. In pulsed mode one insulated-gate bipolar transistor, 1RG4PC50FD (1 RG, 4 PC, 50 FD) can carry 280 A at 600 V, hence two transistors are used in parallel. The wire current is measured with a Rogowski coil. The current waveform is determined by the loop inductance (L $\simeq 40$ μH) and external capacitance ($C = 100$ μF) which produces approximately a half period oscillation ($T/2 \simeq 200$ μs). A full oscillation is prevented, since the transistor stops conducting when reverse biased.

Since the experiment operates at a low duty cycle ($t_{on}/t_{off} = 0.2\%$) the time-average power is relatively low (500 V $\times$ 30 mA $=$ 15 W).

III. EXPERIMENTAL RESULTS

The waveform of the applied wire current and the resultant plasma density near the wire are presented in Figs. 3(a) and 3(b). During the current rise a density peak grows and propagates away from the wire. It is followed by a drop in

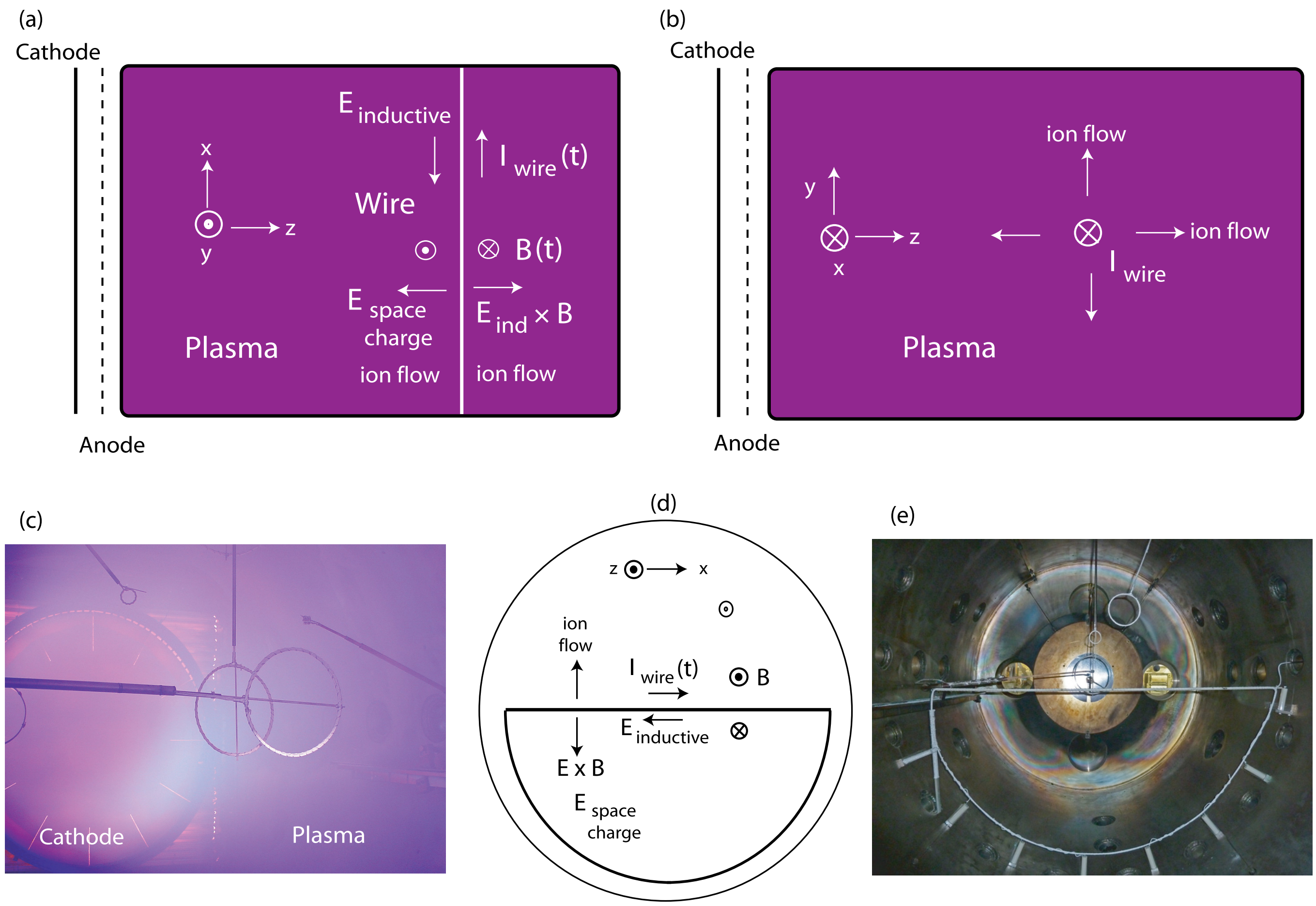

FIG. 1. Schematic of the experimental setup. (a) Side view of the discharge in the x-z plane. The wire is in the x-direction and carries a pulsed current which produces the fields and flows indicated. (b) The same diagram in the y-z plane showing the radial expulsion of plasma from the wire. (c) A picture of the plasma with the 1 m diam cathode in the background. Loop antennas are for different experiments. (d) End view of the setup showing the current closure of the wire by a half circular loop near the bottom chamber wall. (e) Picture of the open chamber showing the wire loop.

density which is most pronounced near the wire. Prior to the peak the density is constant.

The peak is due to the outflow of the plasma, which adds to the uniform background plasma. It is not a decaying sound wave or a transient burst of ions. Following, the peak all ions are still flowing radially outwards, otherwise the density would not continue to drop. The outflow decreases with distance from the wire, since the electric field decreases. The outflow also ends when the current reaches the maximum, since the inductive electric field vanishes.

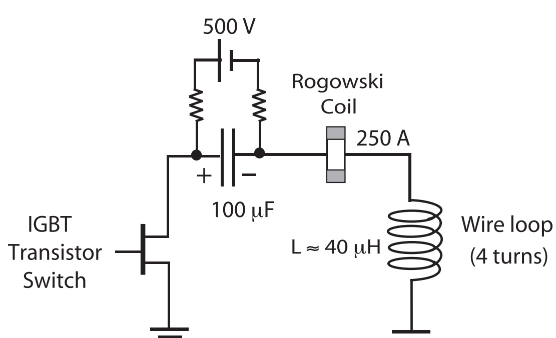

FIG. 2. Schematic of the pulsing circuit.

After the maximum the current gradually decreases, which reverses the sign of the inductive field and produces a slow refilling of the density hole ($100 < t < 160$ μs).

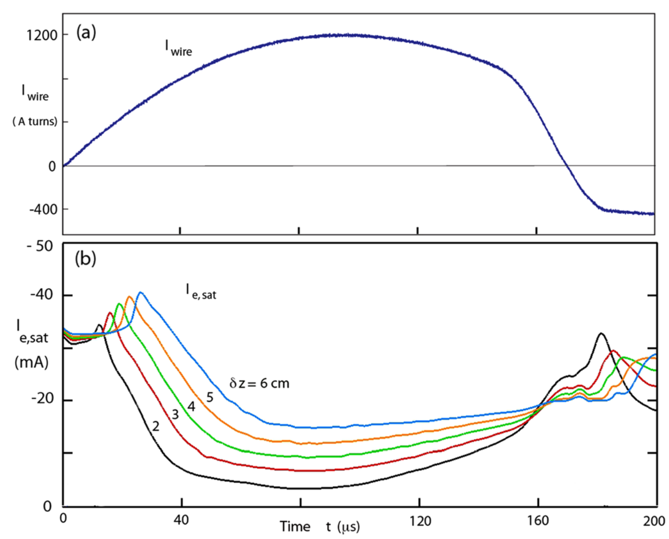

FIG. 3. Density formation by pulsed current. (a) Wire current waveform. (b) Probe saturation current ($\propto$ plasma density) vs time at different distances from the wire. The first peak is the ejected plasma front, followed by a drop in density and gradual refilling after $I_{wire,max}$.

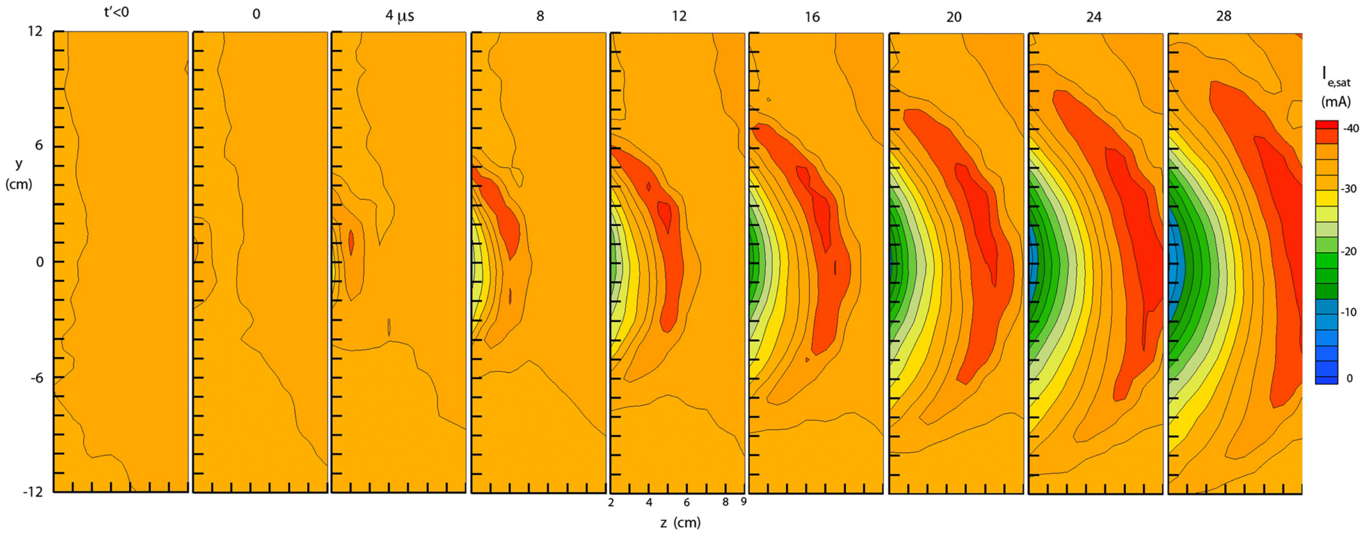

FIG. 4. Time evolution of the plasma expulsion. Contour profiles at different times after applying a rising wire current. Density depletion (green) is preceded by an enhancement (red) which propagates supersonically away from the wire.

However, when both the current and the electric field reverse sign ($t > 170\ \mu$s) the plasma is again expelled from the wire.

The plasma dynamics has also been mapped in two dimensions and time. Figure 4 shows a set of contour maps in the right half plane of the wire at different times after the start of the wire current. The first contour map, which is taken prior to the current pulse shows that the plasma is uniform. In time a growing crescent-shaped density peak propagates radially outward. A density depression is left behind. The growing density peak is caused by ions which catch up with the slower expanding front. The ion velocity increases the longer the ions reside in the radial space charge electric field. The ions should also be accelerated by the inductive electric field along the wire but this motion does not explain the plasma expulsion.

During the rise time of the current ($t \simeq 100\ \mu$s) the expansion front travels radially about 25 cm from the wire. During this time a deep density depression develops which is shown in three-dimensional surface plots in Fig. 5. If the density layer is thinner than the expansion width a "hole" for communication should open up. The depression depth and width depend on the duration of the current rise and the peak current. Neglecting, the wire resistance the rise time $T \propto (LC)^{1/2}$ depends on the circuit inductance L and capacitance C, while for given L and C the peak current can be increased with applied voltage, $I = V(C/L)^{1/2}$.

In the experiment leading to Fig. 5, a weak axial magnetic field was applied ($B_0 = 5$ G). It produces an initial $\mathbf{E}_{ind} \times \mathbf{B}_z$ electron drift in y-direction which expels ions asymmetrically creating a low density channel in the -y direction. Thus, a bias magnetic field can be used to shape the plasma expulsion.

The shape of the current loop determines the shape of the density depression, but does not alter the basic plasma

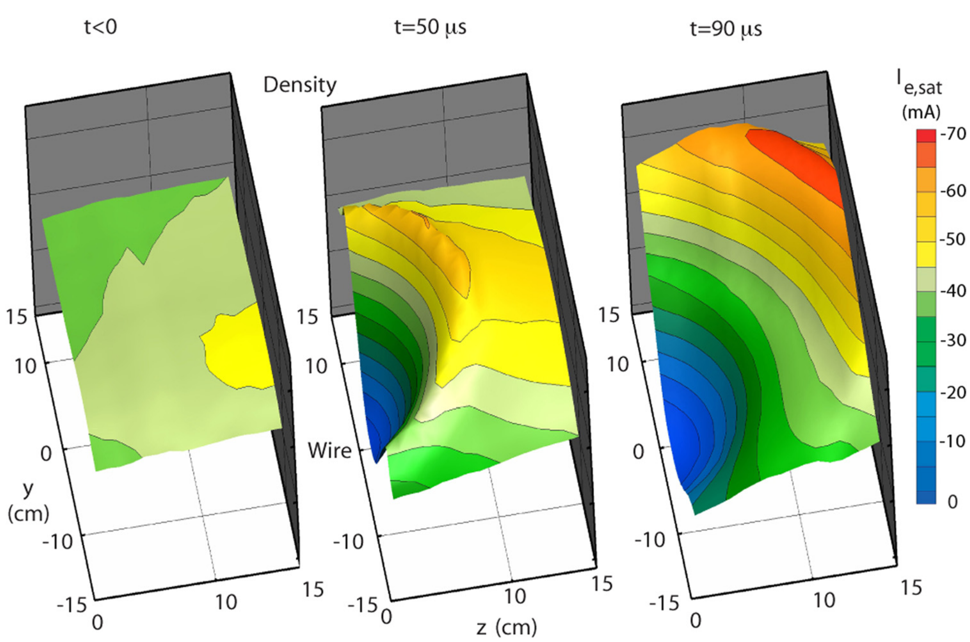

FIG. 5. Three dimensional plots of density profiles at different times after applying a rising wire current. A deep density depression develops around the wire at y = z = 0.

dynamics. A density cavity is also observed for a circular current loop as summarized in Fig. 6. The total field of the loop and the opposing axial field produces two null points on axis away from the loop. Near the coil the field is dominated by the pulsed coil current [Fig. 6(a)]. A picture of a similar loop in plasma was shown in Fig. 1(c). The rising current creates a radially expanding density front which leaves a depletion near the wire [Fig. 6(b)]. The density front propagates above the ion sound speed, 3×10^5 cm/s [Fig. 6(c)].

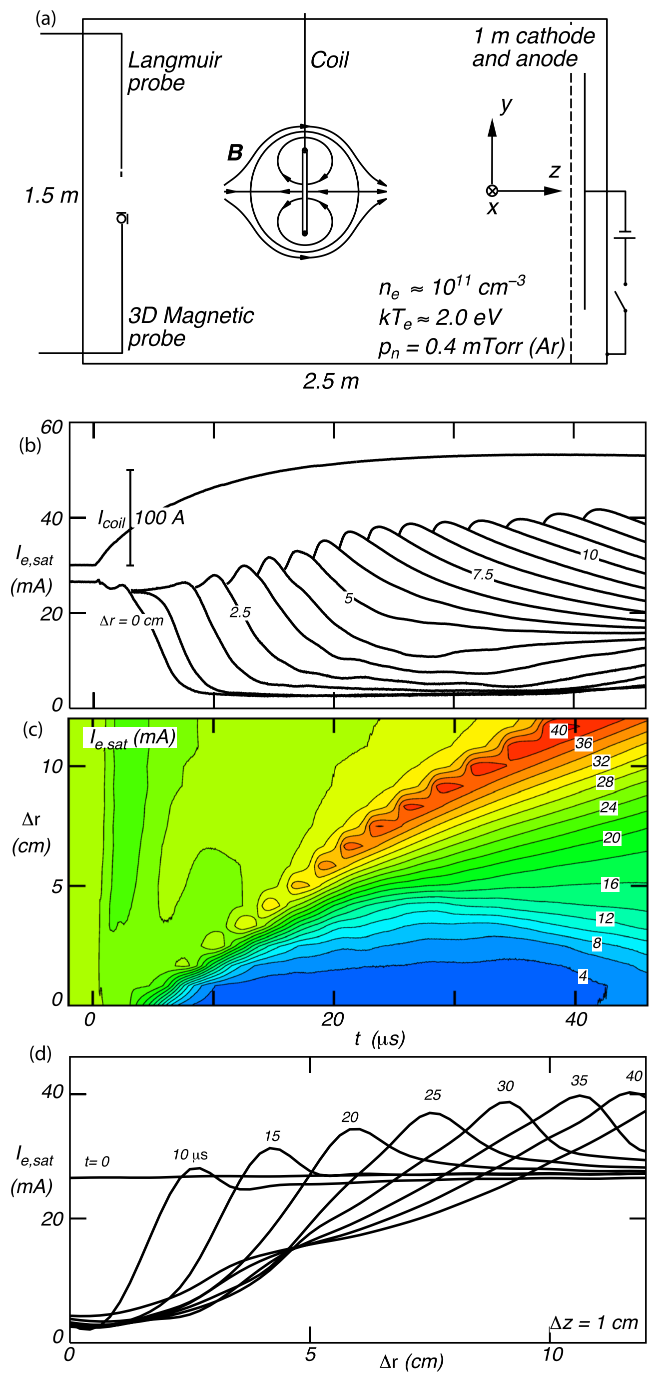

FIG. 6. Density depression created by a pulsed current through a circular wire loop of 30 cm diameter. (a) Schematic setup. (b) Coil current and density vs time at different distances from the wire. (c) Contour plot of the radial density profile vs time. The expansion front propagates radially at a speed of 3×10^5 cm/s. (d) Density vs radial distance from the coil at different times, showing the density depletion near the wire.

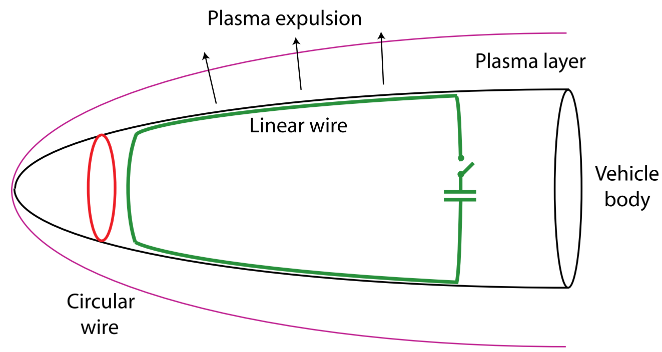

FIG. 7. Possible wire arrangements on a supersonic vehicle. The wire has to be close to the surface in either linear (green) or circular (red) geometry. The plasma layer will be expelled radially from the wire. A conducting vehicle body needs to have an electrical break normal to the wire to avoid short-circuiting the pulsed current.

Radial density profiles are shown at different times [Fig. 6(d)]. In 3D, the density perturbation has the shape of a doughnut with the density minimum at the wire.

IV. PROPOSED IMPLEMENTATIONS

The hypersonic vehicle is surrounded by a layer of plasma which creates the blackout. The objective is to reduce the density and thickness of this layer so as to receive/transmit signals with frequencies at or below the plasma frequency of the layer. In order to reduce the density, the ions have to be expelled radially faster than they are supplied, i.e., faster than the vehicle motion. The observed radial expansion is faster than the ion sound speed $c_s = (kT_e/m_i)^{1/2}$, which in turn is much faster than the neutral sound speed, hence is sufficient to dilute the plasma layer.

The current carrying conductor has to be close to the vehicle's surface. Two possible wire arrangements are sketched in Fig. 7. The conductor can either be straight and along the axis or circular around the axis of the vehicle. For a hemispherical plasma expulsion the density will be lowered since the particles are distributed over a larger volume. Shaped density expulsions with a weak dc bias magnetic field can open up a window of transparency. Although during the plasma expansion the front forms a density enhancement it is a thin layer which a microwave can tunnel through with little attenuation.

In order to avoid induced eddy currents in a conductive vehicle wall there has to be an electrical break normal to the wire. Microwave antennas are placed inside the vehicle close to the wire for transmission/reception of signals through the depleted plasma layer. Multiple antennas with different orientations along the wire enhance the information.

The depletion occurs only during the current rise which may have a duration of $\Delta t < 1$ ms. Although this is a long time for microwave signals the wire pulses need to be repeated periodically for the duration of the blackout. For a repetition time of 1 s the average power requirement is only a few 10's of Watt.

V. CONCLUSION

A simple method for depleting a plasma layer has been observed in a laboratory plasma. It involves a time-varying magnetic field produced by a pulsed current in conductors immersed in a plasma. The magnetized electrons are repelled, set up a Hall electric field which expels the unmagnetized ions away from the conductor. The plasma is governed by EMHD physics rather than MHD which is only valid when the ions are also magnetized.

The observed plasma depletion suggests a method for mitigating the blackout problem on hypersonic vehicles. Conductor is placed at the surface of the vehicle and expels the ions radially away from it. The density depletion allows transmission of normally evanescent waves to antennas on the vehicle. The communication is created for short periods which are repeated during the blackout period.

The density reduction by $\mathbf{E} \times \mathbf{B}$ flows has been considered earlier.[11–14] It requires a plasma source and strong magnetic fields. It can operate in steady state but the present pulsed method is simpler and lighter. Both schemes should be tested in space.

ACKNOWLEDGMENTS

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