HF-driven currents in the polar ionosphere

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Received 7 March 2011; revised 13 April 2011; accepted 14 April 2011; published 21 June 2011.

[1] Polar ionospheric heaters have generated ULF/ELF/VLF waves by modulating the auroral electrojet at D/E region altitudes. We present theoretical/computational results indicating that modulated F-region HF heating can generate ionospheric currents even in the absence of electrojet currents. The ELF currents are driven in a two-step process. First, the pressure gradient associated with F-region electron heating drives a local diamagnetic current. This acts as an antenna to inject Magneto-Sonic (MS) waves in the ionospheric plasma. Second, the electric field of the magneto-sonic wave drives Hall currents when it reaches the E region of the ionosphere. The Hall currents act as a secondary antenna that injects waves in the Earth-Ionosphere Waveguide below and Shear Alfven waves upwards to the conjugate regions. The paper examines the scaling and limitations of the concept and suggests proof-of-principle experiments using the HAARP ionospheric heater. **Citation:** Papadopoulos, K., N. A. Gumerov, X. Shao, I. Doxas, and C. L. Chang (2011), HF-driven currents in the polar ionosphere, *Geophys. Res. Lett.*, *38*, L12103, doi:10.1029/2011GL047368.

1. Introduction

[2] Ionospheric heaters in Polar Regions (EISCAT, HAARP, HIPAS) generated electromagnetic waves in the ULF/ELF/VLF range [*Belyaev et al.*, 1987; *Rietveld et al.*, 1987; *Barr and Stubbe*, 1991; *Moore et al.*, 2006; *Papadopoulos et al.*, 1990, 2003, 2005] in a concept termed by the EISCAT group as the Polar Electrojet (PEJ) antenna. The PEJ antenna requires an ionospheric heater located under regions of naturally driven D/E region currents. Simply the PEJ antenna operates as following: In the presence of an electrojet current periodic electron heating in the Hall region of the lower ionosphere reduces the conductivity of the heated spot building oscillatory polarization charges at the boundaries. This acts as a Horizontal Electric Dipole (HED) at the modulation frequency. The HED excites the Earth-Ionosphere Waveguide (EIW) from above while the current closes by launching upwards helicon (whistler) waves carrying field-aligned current [*Zhou et al.*, 1996]. A major problem with the PEJ is its reliance on the presence and strength of the electrojet current. This restricts not only the location of the heater but makes their generation highly unpredictable.

[3] This letter describes a new concept for driving modulated ionospheric currents that result in injection of ELF/ULF waves in the EIW and the radiation belts without relying on the presence of electrojet currents. Since in this regime the heater drives its own currents in the ionosphere we refer to it as Ionospheric Current Drive (ICD). Using ICD, waves in the ULF/ELF range can be generated even by facilities located away from electrojet regions, such as the upcoming Arecibo heater, as well as in electrojet regions even in the absence of electrojet currents. The letter is organized as following: After a brief outline of the ICD physics and its differences with the PEJ, the letter presents comprehensive simulations of the process that were and are being used to conduct proof-of-principle experiments using the HAARP facility. The letter concludes with a discussion of future experiments using the Arecibo HF heater currently under construction, as well as the advantages of ICD at latitudes near the dip equator.

2. Physics Considerations

[4] The physics underlying the novel concept is illustrated in Figure 1 for the general case of a density gradient at angle α to the magnetic field. However, our modeling will focus on the cylindrically symmetric case with α = 0. While this case is strictly applicable to high latitudes, the models can also guide us to the ICD physics expected at equatorial and mid-latitudes. The ground signature of the ICD driver involves two steps:

[5] 1. The first step involves the generation of an oscillatory diamagnetic current J with angular frequency ω in the heated F-region. It is given by [*Spitzer*, 1956, p. 24]

$$\vec{J}(t) \approx \frac{\vec{B} \times \nabla \delta p}{B^2} \exp(i\omega t) \tag{1}$$

Here δp is the modified F-region pressure due to the HF electron heating, and $\vec{B}$ the ambient magnetic field. Assuming for simplicity that a cylinder of radius R and length L along the magnetic field represents the heated volume, the periodic modulation results in a magnetic moment $\mathbf{M_o}$ given by

$$\vec{M}_o(t) = \hat{b}(\delta p_\perp / BR)(RL)(\pi R^2) \exp(i\omega t) = \hat{b} M_o \exp(i\omega t)$$
$$M_o = \delta p_\perp V/B \approx \varepsilon_a / 2B \tag{2}$$

In equation (2) V is the heated volume and ε_a is the total energy absorbed during the on-modulation time. The magnetic moment is aligned with the magnetic field direction $\hat{b}$ and as a result will radiate Magneto-Sonic (MS) waves. This mode propagates isotropically [*Kivelson and Russell*, 1995] in the ionospheric plasma and will intercept the E-region at a distance and extent that depends on α.

[6] 2. The second step involves the interaction of the electric field of the MS wave with the Hall conductivity of the lower ionosphere. The Hall current, driven by the electric field of the MS wave generates ground magnetic field signatures and drives Shear Alfven (SA) waves upwards

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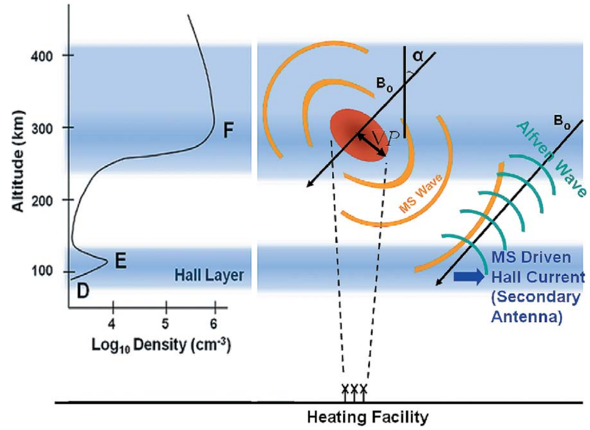

Figure 1. Schematic of the Ionospheric Current Drive (ICD) physics. Periodic F-region heating leads to an oscillatory diamagnetic $\vec{B} \times \nabla p_\perp$ current and an associated field aligned magnetic moment M that radiates isotropically MS waves. The interaction of the MS waves with the Hall region generates a Hall current locally and couples them to the SA mode. The process injects ELF waves in the EIW and SA waves along the magnetic tubes that intercept the interaction region.

along the magnetic tube that intersects the interaction region, in a fashion similar to the PEJ.

[7] In essence while the PEJ antenna relies on D/E oscillatory Hall currents driven by modulating the conductivity in the presence of an ionospheric electric field, ICD drives its own oscillatory electric field by F-region modulation to achieve the same effect.

3. Two-Dimensional Modeling of ICD

[8] We use a 2D ionospheric code in cylindrical geometry to study the ICD by F-region heating. The code is based on the model developed by *Lysak* [1997] to study Alfven wave propagation through the ionosphere and modified to include (i) the generation of MS waves by the pressure driven diamagnetic current, and (ii) relaxation equation for the parallel current (J_z) to provide smooth matching with the atmospheric region. Lysak's formulation provides physics clarity by separating the SA wave mode from the MS by taking advantage of the fact that the curl of the electric field of the SA wave has a zero component parallel to the magnetic field, while the MS has a divergence free perpendicular electric field. Following *Lysak*'s [1997] procedure defining $Q = \nabla_\perp \cdot \mathbf{E}_\perp$, $M = (\nabla_\perp \times \mathbf{E}_\perp) \cdot \mathbf{i}_z$, $J_z = (\nabla_\perp \times \mathbf{B}_\perp) \cdot \mathbf{i}_z$ and adding the source due to the pressure gradient driven by the F-region HF heating we can derive the basic equations of our model as

$$\left(\varepsilon\frac{\partial}{\partial t} + \sigma_P\right)Q = -\sigma_H M - \frac{\partial J_z}{\partial z},$$
$$\left(\varepsilon\frac{\partial}{\partial t} + \sigma_P\right)M = \sigma_H Q - \frac{1}{\mu_0}\nabla^2 B_z + \frac{1}{B_0}\nabla_\perp^2 \delta p_\perp,$$
$$\frac{\partial B_z}{\partial t} = -M, \quad \mu_0\frac{\partial J_z}{\partial t} = -\frac{\partial Q}{\partial z} + \nabla_\perp^2 E_z, \quad \left(\varepsilon_0\frac{\partial}{\partial t} + \sigma_\parallel\right)E_z = J_z. \tag{3}$$

Here σ_H, σ_P, and $\sigma_\parallel$ are the Hall, Pedersen, and parallel conductivities, and $\varepsilon(z)$ is the plasma dielectric constant given by

$$\varepsilon(z) = \frac{c^2}{V_A^2(z)\left[1 + \nu_{in}^2(z)/\Omega_i^2\right]} \tag{4}$$

In equation (4) $V_A(z)$ is the Alfven speed, $\nu_{\rm in}(z)$ the ion-neutral collision frequency and $\Omega_{\rm i}$ the ion cyclotron frequency. Notice that as long as the plasma density gradient is parallel to the magnetic field and the effect of collisions in the F-region is neglected, the HF heating drives only the MS wave. Accurate modeling of the F-region source depends on proper modeling of the collisional as well as anomalous absorption and heat losses in the F-region as a function of the F-region plasma and HF characteristics. These are subjects of ongoing research and beyond the scope of this letter. For our study we assumed a simple pressure source given by

$$\delta p_\perp(r,z,t) = n(z)k_B T_{\rm mod}\tanh^2(t/D_t)[1+\cos(\omega t)] \exp\left[-\frac{r^2}{D_r^2} - \frac{(z-z_{\rm max})^2}{D_z^2}\right] \tag{5}$$

This term describes F-region heating near the F-peak located at $z_{\rm max}$ with average transverse electron temperature $T_{\rm mod}$ over the modified region, assumed to have Gaussian profiles with widths D_r and D_z in radial and z directions, respectively. The transient heating driver has a rise time ~D_t. Notice that the interaction strength scales linearly with the value of $T_{\rm mod}$. An additional modification of Lysak's model is the computation of the magnetic fields expected on the ground. It is accomplished without any change in the solver since equation (3) reduce to Maxwell's equations for isotropic conductive media with permittivity ε_m and conductivity σ_m simply by setting $\varepsilon = \varepsilon_m$, $\sigma_H = 0$, and $\sigma_P = \sigma_\parallel = \sigma_m$. We conducted the simulations in a simulation domain containing both ionosphere and atmosphere. On the ground, perfect conductor boundary conditions were imposed ($Q = M = B_z = \partial J_z/\partial z = 0$).

[9] The overall model is three-dimensional, while in cylindrical coordinates (r, θ, z) the dependence on the angular coordinate θ can be neglected for the axisymmetric driving term and transverse homogeneity. The model explicitly advances the MS and SA waves, which are coupled through the Hall conductivity. The most important restriction of the horizontal homogeneity assumption is neglect of the oblique nature of the ambient magnetic field on the wave propagation at large distances. The simulations were obtained using the discrete Fourier-Bessel transformation the radial coordinate and the Crank-Nicholson scheme with respect to t and z for each radial mode. The Courant condition does not limit the stability of the scheme and equation (3) can be solved even in the atmospheric region to satisfy the appropriate ground boundary conditions.

4. Computational Results

[10] Simulations were conducted for different ionospheric models and heating source parameters. In this letter we present only key results that describe the physics of the interaction and can be used as guides for experiments using HAARP and other ionospheric heaters. The ionosphere was

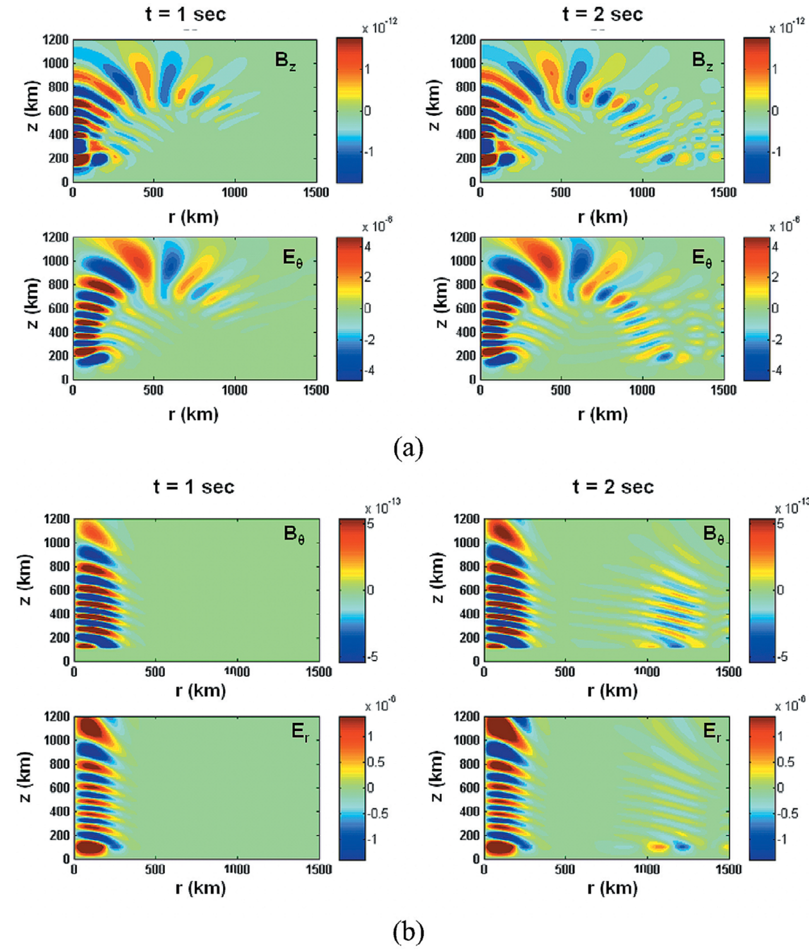

Figure 2. (a) MS components B_z and E_θ at times 1 and 2 sec following heater turn on for 10 Hz modulation of the HF heater. B_z and E_θ are of units Tesla and V/m, respectively. (b) Same as Figure 2b but for the SA wave components.

modeled as Chapman profile with maximum density of 5 × 10^{10} #/m^3 located at z_{max} = 300 km, corresponding to a minimum Alfven speed of ~1000 km/sec and 120 km scale height. The Hall conductivity dominated region extended from 80–120 km. In all cases the F-region source was modeled with D_t = .25 sec, D_r = 100 km, D_z = 20 km and T_{mod} = 5000 K. Such parameters are consistent with HAARP operating at full power at frequency between 3–5 MHZ.

[11] We present below first results showing the generation of MHD waves by ICD in the ionosphere. This is followed by a discussion of the currents induced in the Hall region and the structure of the fields measured on the ground in the near zone. Figure 2a shows the evolution of the MS components (B_z, E_θ) for 10 Hz modulation at t = 1 sec (Figure 2a, left) and 2 sec (Figure 2a, right). It is clear that the MS wave generated at the source region (300 km) propagates downwards as well as upwards. The E_θ field penetrates the E-region first below the source and subsequently at a distance in excess of 1000 km following its reflection from the density gradient located above z = 300 km. In addition to the MS wave reflection from the E-region the interaction results in the conversion of part of the MS into SA wave. This is seen in Figure 2b, which show the SA wave components at t = 1 sec and 2 sec. A source of SA waves appears at an altitude between 90–120 km below the F-region source displaced laterally by 100–150 km. It results in guided propagation of SA waves confined in a radial distance of the order of 150–200 km from zenith. Focusing on Figures 2a (right) and 2b (right) we note that the impact of the reflected MS wave at a distance of 1000 km created similar SA wave injection and ground signature phenomena to the ones near the HF source albeit at a much lower amplitude. Of course at the 1000 km location the ambient field will not be vertical. However, we expect that qualitatively the physics will be similar. Experiments to detect this effect are on planned. The secondary antenna currents and the ground magnetic signature are shown in Figure 3. Figure 3a shows the Hall currents induced in the E-region (within 90–120 km altitude) by the electric field of the MS and SA waves. It clearly elucidates a key aspect of the ICD. Namely the generation of a secondary antenna in the E-region that acts in a fashion similar to the PEJ to inject ELF waves in the EIW and helicon waves towards the conjugate regions. The dominant current is the J_θ current. The amplitude of the dominant component of the ground magnetic field B_r associated with secondary antenna is shown in Figure 3b. Notice that the peak value of approximately .3 pT is displaced by more than 150 km from the heater location, consistent with the magnitude and azimuthal distribution of the Hall current shown in Figure 2a. Both effects are consistent with ongoing

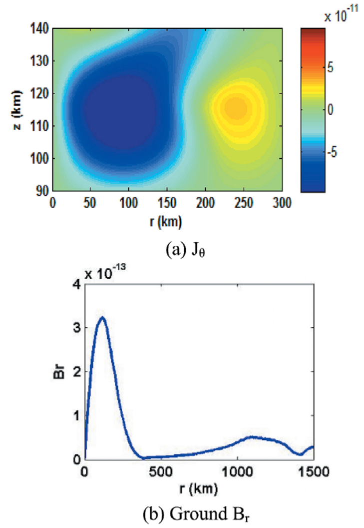

Figure 3. Results of the 10 Hz simulation showing (a) the dominant J_θ current (A/m^2) in the E-region within an altitude 90–120 km and (b) the ground magnetic field B_r (Tesla) in the near zone.

preliminary F-region experiments at HAARP (C. L. Chang, private communication, 2011). Notice that the Hall current has introduced a 90 degree rotation as compared to the magnetic field above the ionosphere as predicted early by *Hughes* [1974].

[12] A number of simulations were conducted for modulation frequencies between 1–20 Hz. The overall qualitative results with respect to the ground field and the secondary antenna in the near zone are similar to the 10 Hz results shown above. We should however mention that frequencies between .5–5 Hz, have much better lateral propagation properties since they represent MS modes guided in the Alfven duct as discussed extensively by *Greifinger and Greifinger* [1968] for the Pc1 micro-pulsation range. An example of this case is shown in Figure 4 for the modulation frequency of 2 Hz. The good ducted propagation of the MS wave near the minimum of the Alfven speed is clearly seen Figure 4 (top), while the SA wave remains confined close to the excitation region (Figure 4, bottom). The induced E-region current J_θ as well as the ground field in the near zone do not exhibit any qualitative differences with the 10 Hz case. Animations comparing the 2 Hz and 10 Hz simulations and illustrating the temporal dynamics of the ICD can be found in the auxiliary material of the paper.[1]

5. Concluding Remarks: Implications for Equatorial and Other Heaters

[13] The letter presents the first model describing current drive in the ionosphere by using modulated HF heating of the F-region. The results indicate that F-region heating drives MS waves that propagate isotropically from the source. Their interaction with the Hall region generates Hall currents that acting as secondary antenna injecting ELF waves in the EIW and SA waves along the magnetic tube that penetrates the modified region. It is interesting to speculate on the implications of the results to heaters located at other latitudes.

[14] We first examine the case of the dip equator (α = 90°), such as being the case if a heater was available in Jicamarca, Peru. Referring to Figure 1, as well as Figure 4 we note that the entire MS front will intercept the E-region directly underneath the heated spot, over a region of more than 200 km in width generating a giant secondary antenna. Furthermore, due to the Cowling effect [*Kelly*, 1989] the E-region conductance is almost two orders of magnitude larger than in the auroral zone (400–500 S vs. 5–10 S). Since the Hall current and the ground magnetic field are proportional to the electric field and the large conductance of the E-region, we expect that MS waves excited in the F-region by modulated heating at the upper hybrid frequency and incident in the E-region will be significantly more efficient in exciting the EIW. We next address the mid-latitude case, such as is the case of the Arecibo heater, currently under construction. In this case the conductance is not significantly higher and we do not expect significantly higher efficiency. For Arecibo $\alpha \approx 65°$ and the MS interception of the E-region will extend to range from above the heater to approximately 300–350 km in lateral direction. We expect that the secondary antenna driven over this region will inject SA waves upwards into the inner radiation belt providing an important tool to study interaction with trapped protons in conjunction with the Radiation Probes. Furthermore it could provide a natural explanation for an F-region experiment [*Ganguly et al.*, 1986] conducted more than 25 years ago, whose observations defied theoretical explanations. In this experiment F-region heating at 5 MHz using the Arecibo heater modulated at 3 and 5 Hz, resulted in detection of ground magnetic field signatures at these frequencies with amplitude between at .1–.3 pT/$\sqrt{Hz}$ at nearby Mona island.

[15] Before closing we should caution the reader that the cylindrical code, while facilitates the numerics and interpretation of the results, it prevents incorporation of a potential direct F-region SA wave source. Such a source has been addressed by *Papadopoulos and Chang* [1985] for D/E region heating. This source emerges by noting that for an equilibrium along the magnetic field it requires that over the

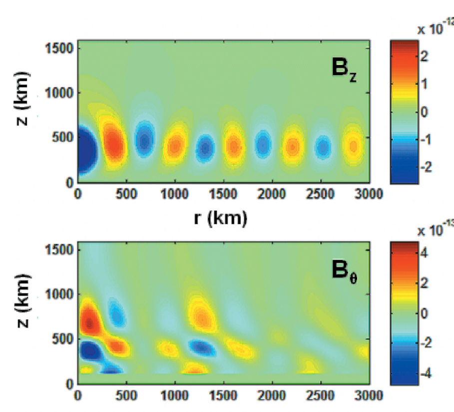

Figure 4. The magnetic field components of the (top) MS (B_z) and (bottom) SA (B_θ) waves for 2 Hz HF heater modulation at time 4.875 sec.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047368.

heated region parallel to B, $E_p = \nabla n T_p/(en)$. An irrotational electric field oscillating with the parallel electron temperature T_p emerges if $\nabla \times E_p = \nabla \times \frac{k_B(\nabla n T_p)}{en} \neq 0$. This can drive directly a SA wave given by $\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \approx \frac{k_B}{e} \frac{1}{L_N} \frac{T_p}{L_p} \sin \alpha$, where L_N is the ambient density gradient length (~100 km) and L_p the field aligned size of the heated region. We are developing a code applicable for values of $\alpha \neq 0$. However, preliminary estimates indicate that its effect will be negligible unless $f/Hz \ll \sin \alpha$. Furthermore, this will be an effect that will be added to MS generation of SA waves.

[16] **Acknowledgments.** The authors greatly appreciate numerous discussions with B. Eliasson, A. S. Sharma, G. Milikh and J. Labenski and A. Vartanyan. The work was supported by ONR MURI grant N000140710789 at the University of Maryland, College Park and by DARPA-DSO under contract HR0011-09-C-0099 to BAE Systems.

[17] The Editor thanks I. Rae and an anonymous reviewer for their assistance in evaluating this paper.

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