Efficiency Scaling for Ionospheric ELF/VLF Generation

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Abstract: Using experimental measurements and theoretical analysis, it is shown that the HF/ELF conversion efficiency is controlled by the timescale for electron temperature saturation. This is a function of the heater ERP and frequency and the ionospheric electron density profile. For the current HAARP parameters this corresponds to frequencies between 2 and 4 kHz. Efficiency optimization techniques as applied to the projected upgrading of the HAARP heater to its design power of 3.6 MW are discussed.

A most fascinating and important property of the active ionosphere is its potential to act as a frequency transformer that converts HF power injected from a high power HF transmitter into the ionosphere, into coherent lower frequency VLF/ELF/ULF waves. The conversion principle relies on modulating the electrojet currents in the ionospheric D and E regions by using amplitude modulated HF heating. The low frequency fields subsequently couple to the earth-ionosphere waveguide, while a fraction of their power upwards towards the magnetosphere. Despite several years of theoretical and experimental work, many scientific and technical issues remain unresolved. Understanding the physics underlying the low frequency wave generation is important in increasing the HF to ELF conversion efficiency and utilizing the technique for ionospheric diagnostics.

A puzzling feature in the results of the experiments conducted using the EISCAT and the HAARP ionospheric heaters, has been the variation of the conversion efficiency with ELF/VLF frequency and the unusually large relative amplitude of the harmonics. Prominent features of the data are:

1. Enhanced efficiency relative to the neighboring frequencies at 2 kHz and its harmonics.
2. Maximum efficiency in the frequency range between 2-4 kHz. Efficiency proportional to the frequency f between 2 kHz and 500 Hz. Weak increase in efficiency between 500 and 100 Hz. Efficiency proportional to 1/f between 4 and 10 kHz.
3. Harmonics with significant relative amplitudes up to ten or larger are present. The amplitudes of the harmonics are much higher than expected from Fourier analysis of the HF heating waveforms.

These basic features are seen consistently in experiments using heater facilities and taken under different heating parameters and ionospheric conditions. We believe that they are intrinsic features representatives of the ongoing non-linear physics. As discussed previously [1-4] and in the absence of propagation effects the conversion efficiency depends on the value of the ambient electric field in the modified region and the spatio-temporal waveform of the modified conductivity in response to the HF heating pulse. Since the first factor, that controls the maximum value of the modified current, is beyond our control, our investigation focused on understanding the physics of the second factor. We present below the first temporally resolved ELF/VLF waveforms measured during modulated ionospheric heating. The results are compared with theoretical models and their implications discussed.

1. EXPERIMENTAL RESULTS

The data presented below were obtained using the HAARP heater in Gakona, Alaska, during two campaigns [5]. In all the results presented here the heater operated at 3.3 MHz, X- mode with power 960 kW and ERP 73 dBW. Since we are interested in near field effects the ELF/VLF data were recorded at a diagnostic trailer site located 12 km away from the heater. The magnetic fields were measured with EMI BF-6 sensors oriented along the magnetic NS and EW directions. The sensor output was digitized at 24-bit resolution with 48 kHz sampling frequency, giving temporal resolution of 20 μsecs in the measured ELF/VLF waveform. Two modes of operation were implemented. The first involved ELF/VLF generation using square wave HF amplitude modulation between 100 Hz and 10 kHz. The second mode involved short pulse HF heating at a 20 Hz rate with pulse length corresponding to half the period of the ELF/VLF waves generated in the first mode.

Figure 1 shows temporally resolved waveforms for the dominant magnetic field component (NS) for the frequency range from 10.0 to .1 kHz. Two things are apparent. First, the peak value of amplitude is minimum at 10 kHz. The peak value increases at lower frequencies and reaches a saturation value at a frequency of 4 kHz. Second, the waveforms in the VLF range have significant power in the fundamental. However, they deteriorate significantly at the ELF range (1 kHz and below). Notice that in this frequency region the waveform is composed of a spike with duration of .125 msec at the beginning of each cycle, followed by a plateau of approximately 1/3 of the peak amplitude for the remaining pulse. As a result, at low frequencies, the HF to ELF conversion is low for most of the cycle. Furthermore, a Fourier analysis of the waveforms is consistent with the presence of harmonics with anomalously high amplitude.

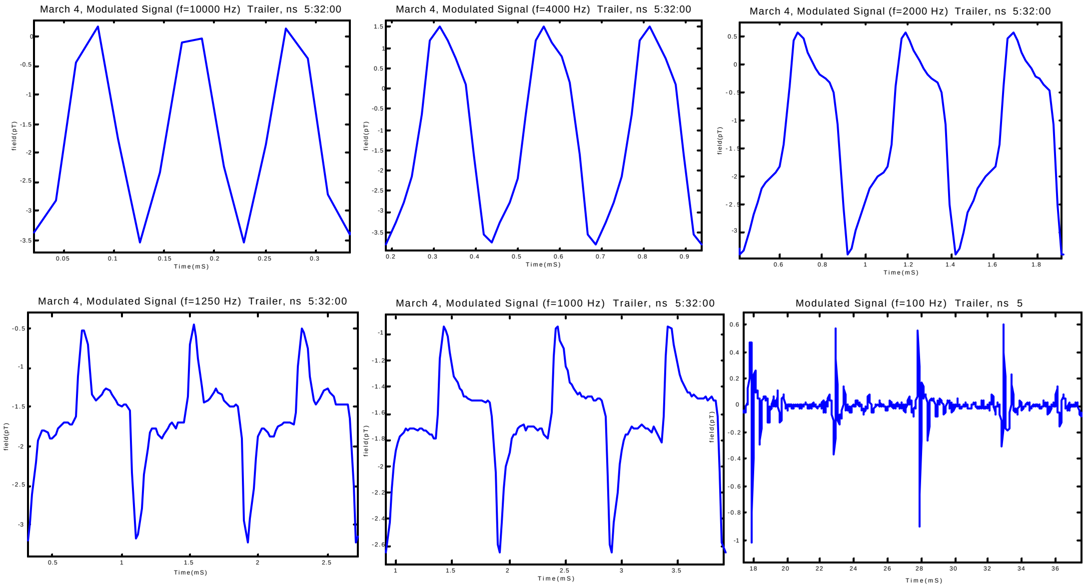

Figure 1. Temporally resolved waveforms measured near the heater for square pulse modulation at frequencies 10.0, 4.0, 2.0, 1.25, 1.0 and .1 kHz

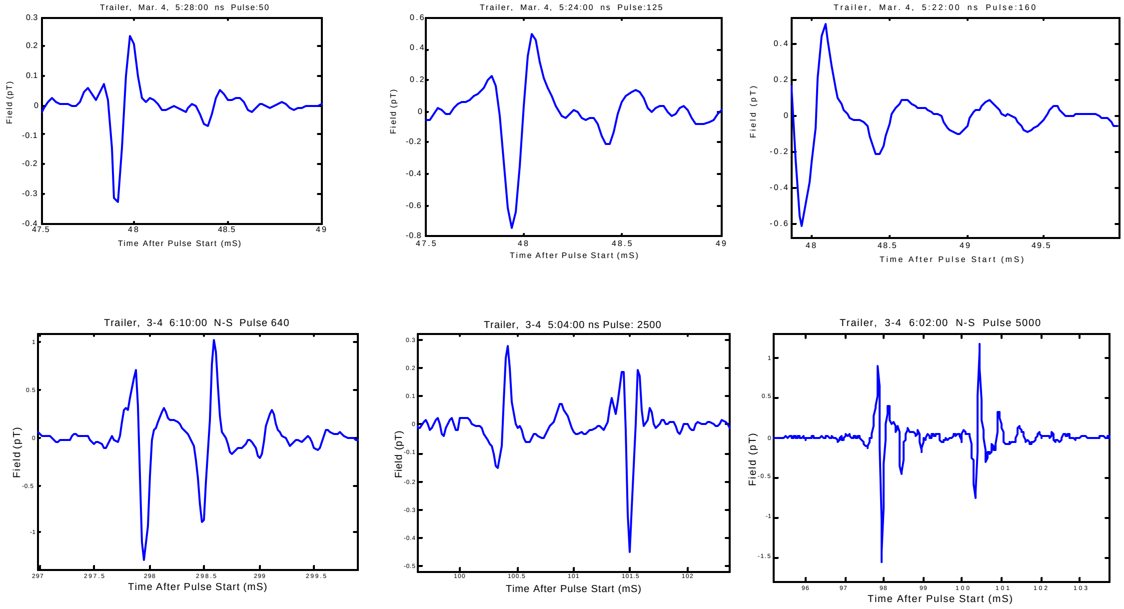

Figure 2. Short pulse waveforms for square pulse with duration .050,.1, .125, .160, .640, 2.5, and 5.0 msecs

The features as well as the physics represented by the waveforms of Figure 1, can be clarified by examining the waveforms recorded during the second experimental mode shown in Figure 2. In this mode, the period between pulses was 50 msec, much longer than the ionospheric relaxation time. In essence, this mode allowed us to measure the Green's function response of the ionosphere as manifested by the magnetic field generation. Referring first to pulses shorter than .25 msecs, corresponding to half periods of frequencies higher than 2 kHz, we note the following. The maximum field amplitude increases essentially linearly with time from .05 msec and reaches saturation at approximately .125 msec. Following turn-off of the pulse the field goes through zero and has an overshoot. The ratio of the overshoot amplitude to the maximum increases with pulse length and approaches unity at pulse lengths of .250 msec. An additional feature present in these data is the presence of weaker peaks with similar form as the driven waveform with a delay time of approximately .5 msec. The last feature was previously reported [1,2] and correctly interpreted as echoes generated by reflection of the original pulse from the ionosphere. In [1] these features have been used to determine the ionospheric reflection height and the reflection coefficient and to determine the heating and cooling times in the D region. For pulses longer than .25 msec the data show the appearance of a plateau in the magnetic field with amplitude approximately .3 of the maximum, similar to the plateau shown in Figure 2 for the ELF range of frequencies. To our knowledge this is first observation of the plateau feature. For pulses longer than .5 msec the echoes feature is superimposed on the plateau. Referring to Figure 2 in [2], we note that the plateau region is either lost in the noise or filtered by a low pass filter. The rest of their waveform is similar to ours.

2. THEORETICAL MODELING

The physics underlying these observations can be understood by referring to theoretical modeling. There are two steps in the computation. The first is to find the spatio-temporal profile of the current j(r,t) induced by the heater by using an HF heating code. The second is to compute the near field at the observation site using retarded potential method [5]. The computations were conducted for different ionospheric conditions using the frequency and ERP used in the HAARP experiments. Figure 3 shows the output of the code along with the observation of the E-W component of the magnetic field detected in the near zone. As shown in reference [5] the magnetic field in the ground can be written as

$$B(t) = A\,\frac{I(t)}{h^2}\left[1 + \frac{h}{c}\,\frac{1}{I(t)}\,\frac{dI(t)}{dt}\right] \qquad (1)$$

where A is a constant, h the absorption height and I(t) the ionospheric current. The important aspect of this equation is that two terms contribute to the value of B; one proportional to the current (shown by the dashed line in Figure 3), and the second proportional to the time derivative of the current (shown by the dotted line). The solid curve shows the combined field. As seen in the figure the theoretical and experimental waveforms are in very good agreement. Figure 3 also reveals the major physics of efficiency scaling; namely that for times shorter than 0.125 msec the time derivative of the induced ionospheric current dominates, while at later times this field approaches zero and the dominant contribution is to the current itself. The experimental waveform shows also a smaller peak, about 20% of the maximum, with 0.5 msec delay, which is due to the reflected signal. This effect is currently not included in the numerical model.

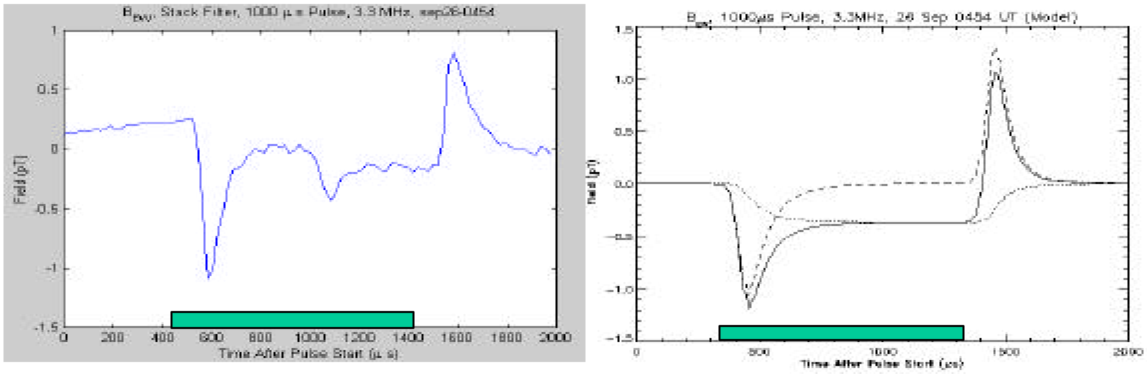

Fig. 3. The observed waveforms shown on the left and the theoretical predictions shown by the solid curve on the right plate

3. CONCLUDING REMARKS

In this paper we presented

- The first set of temporally resolved waveforms for ionospheric generation of ELF/VLF waves.
- The first experimental measurement of the magnetic response (Green's function) of the ionosphere to impulsive RF heating.

The comparison of the experimental results with theory/modeling clearly demonstrates that high efficiency ELF/VLF generation occurs only when the time derivative of the induced current is different than zero, corresponding to the saturation time of the ionospheric temperature. For the current HAARP heater parameters this time scale corresponds to between .15-.3 msecs. As a result the efficiency is optimum in the 2-4 kHz range. This dictates that efficient production at lower frequencies requires new concepts, such as painting, coherent sweeping and other forms of waveform synthesis that take advantage of the fast sweeping capabilities of HAARP and of the high gain/high ERP expected from the projected upgrade of the HAARP heater to 3.6 MW. Preliminary results of such waveform synthesis have produced encouraging results. Finally the results of the short pulse experiments are indicative of the high potential of HAARP for D/E region diagnostics

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