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WAVES GENERATED BY PULSED ELECTRON BEAMS

T. Neubert,* K. J. Harker,* P. M. Banks,* E. G. D. Reeves* and D. A. Gurnett**

**STAR Laboratory, Department of Electrical Engineering, Stanford University, Stanford, CA 94305–4055, U.S.A.*
***Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, U.S.A.*

ABSTRACT

During the Spacelab-2 flight of July, 1985, electron beams (1 keV, 100 mA) square-wave modulated at ELF and VLF were emitted from the space shuttle. The wave fields generated by the beam were monitored by a free-flying sub-satellite at distances up to 300 m perpendicular to the beam. The amplitude of the magnetic and electric fields were modulated by the spin of the satellite. This modulation allows the study of the wave polarization. Results for a 7 min duration beam sequence in which the beam was pulsed at 1.22 kHz are presented and compared with recent predictions for wave-fields stimulated by ideal helical electron beams propagating in a magnetized plasma. It is found that the predicted magnetic field amplitude of the first harmonic of the beam pulsing frequency (below the lower hybrid frequency) is in agreement with observations, however, the predicted and the observed polarizations are entirely different. For the higher harmonic components (above the lower hybrid frequency), theory predicts order of magnitude larger magnetic field amplitudes than observed. It is concluded that the theory does not adequately model the full distribution of the radiating current.

INTRODUCTION

The Spacelab-2 mission of the space shuttle carried the Fast Pulse Electron Generator (FPEG) which was capable of emitting electron beams with the energy of 1 keV and currents at 50, 100 or 150 mA. The beam could be pulsed at frequencies from DC up to several hundred kHz with a rise time of the order of 10^{-7} sec, thereby emitting an almost perfect square-wave modulated beam.

The electromagnetic fields generated by the beam were observed by a Plasma Diagnostics Package (PDP), which carried an array of plasma diagnostics instruments including a wide-band VLF wave receiver. The receiver was connected to either an electric dipole or to a magnetic loop antenna, the two antennas alternating every 51.2 sec. Every fourth magnetic antenna period was substituted with a connection to a Langmuir probe. The receiver was controlled by an Automatic Gain Control (AGC), which assured a roughly constant output signal level and a dynamic range of 100 dB. The receiver scanned a 30 kHz frequency range by selecting bands in the following order: 0-10 kHz (25.6 sec), 20-10 kHz (12.8 sec) and 20-30 kHz (12.8 sec). The output was telemetered in analog form and later digitized at 25 kHz. A more detailed description of the FPEG and the PDP is found in /1,2/.

OBSERVATIONS

<u>Wave Spectra</u>

For four orbital periods the PDP was released as a free-flying sub-satellite to co-orbit with the shuttle out to a separation distance of about 300 m. During one of the magnetic conjunctions between the shuttle and the PDP, the FPEG emitted a 100 mA beam pulsed at 1.22 kHz for a period of 7 min. In Figure 1 is shown the trajectory of the PDP relative to the shuttle with markers for every one minute. The vertical axis is the distance to the PDP measured along the earth's magnetic field, and the horizontal axis the distance perpendicular to the field. The period of the pulsed beam sequence and the antenna switching pattern of the wide-band VLF wave receiver is indicated by shaded areas.

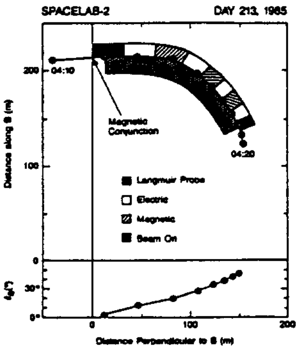

Fig. 1. On the top panel is shown the trajectory of the PDP relative to the shuttle during the pulsed flux-tube connection. The period of beam emission and the wide-band antenna switching pattern are shown by the shaded areas. The bottom panel shows the beam angle to the earth's magnetic field, θ_B.

The shuttle attitude was continually adjusted during this beam sequence so that the initial velocity of the beam electrons was always directed towards the PDP. The imposed variation of the beam pitch angle, θ_B, is shown on the bottom panel of Figure 1.

An example of the of the magnetic wave fields observed in the 0-10 kHz range is shown in Figure 2 at a time when the PDP was located at a distance of about 135 m perpendicular to the beam and 165 m from the shuttle parallel to the beam. The relative signal intensity (the AGC level is not folded in) is color coded showing the fundamental of the pulsing frequency and its odd harmonics as horizontal lines. Also seen are the much weaker even harmonics and background noise in the form of whistlers.

The pulsing duty cycle was 50%, which means that the beam *on* -time equaled the beam *off* -time. The Fourier transform of a square-wave-train with 50% duty cycle has finite amplitude odd harmonics and zero amplitude even harmonics. This feature is reflected in the observed magnetic signal, as reported in /3,4,5/, and are in accordance with theoretical predictions for radiation from pulsed electron beams /6/.

The relative electric field intensity observed at a distance 95 m perpendicular to the beam and 205 m parallel to the beam is shown in Figure 3. Most conspicuous is broad-banded noise and a series of 6 shuttle thruster emissions seen to drastically alter the spectral shape of the noise. The the noise level, integrated over the 10 kHz band, increases during these thruster emissions although the AGC make them appear weaker. The broad-banded noise is stimulated by the pulsed beam emission and is about 40 dB above the natural background noise level. Broad-banded noise of comparable intensity was observed during a DC sequence performed earlier during the free-flight /5,7/.

Wave Polarization

The narrow-band emissions at the harmonics of the pulsing frequency are modulated in amplitude during a spin of the PDP. The modulation of the magnetic signal is seen in Figure 2 as a variation of the color intensity with time. The electric and magnetic antennas

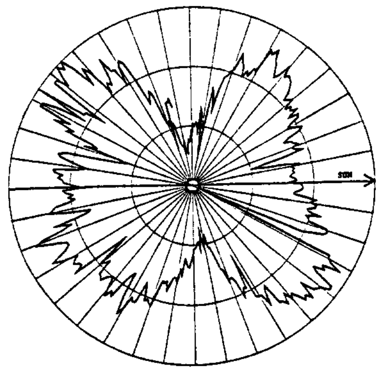

Fig. 4. The amplitude of the first harmonic magnetic field component (also seen in Figure 2) during half a spin period. The phase is shown with respect to a fixed direction in space, namely the projection of the earth-sun vector onto the spin plane.

measured the component of the wave fields in the spin plane. With a spin period of about 13 sec the wave amplitudes were modulation with a period of 6.5 sec. The spin modulation allows us, when the signal is reasonably time-stationary during half a spin, to extend the one-component wave field observation to a two-component observation, namely two orthogonal components in the spin plane. With the complete information of the shuttle and PDP attitudes, the field components can be referred to a coordinate system fixed in space. Figure 4 shows a polar plot of the amplitude of the first harmonic magnetic field component also seen in Figure 2. The radial coordinate is the amplitude observed during half a spin and the phase is shown with respect to a direction fixed in space, namely the earth-sun vector.

In the far field region, the plasma dispersion relation can be used to obtain three components from a one component spin modulated measurement. For example, it is known from the dispersion relation that the magnetic component of whistler waves is circularly polarized. The PDP provides, during a spin, a measurement of the ellipticity of the magnetic field in the spin plane. Thus, in the far field regime, four directions in space of the wave normal, **k**, can in general be found, namely the ones for which the associated circular polarization, when projected onto the spin plane, gives the observed elliptical polarization. Knowing the origin of the waves often leaves just one solution for **k**, and 3 magnetic components are thereby determined from the measurement of one spin-modulated component. However, since the VLF wave observations during the pulsed flux-tube connection were made in the near field region, this avenue of approach is not available. Still, the extra information contained in the spin-modulation is valuable as shown in the next section.

COMPARISON WITH THEORETICAL MODELS

The electromagnetic components of the fields generated by a pulsed electron beam in a magnetized plasma is found in /6,8/. The beam is modeled as an infinite train of square-wave pulses and the radiation is obtained by adding coherently the radiation from each individual electron in the idealized helical trajectory assumed by the beam. The expression for the fields are found without the usual simplifying assumption that the observation-point is in the far field region. However, the expressions contain the contribution to the fields arising from the wave-particle resonance conditions, but not the contribution from the branch cuts in the $\mathbf{k}_\perp$ plane. The solutions are thought to represent surface waves propagating along the beam and to represent approximations to the fields close to the beam (within one perpendicular wave length).

In the following we compare the predictions of /6/ for the first harmonic magnetic component with the observations. It is assumed that the waves and the beam electrons are in Cherenkov resonance (wave fields generated through cyclotron and anomalous cyclotron interactions are evanescent at this frequency, while the wavelenght for the high harmonics are comparable to the Debye length and are

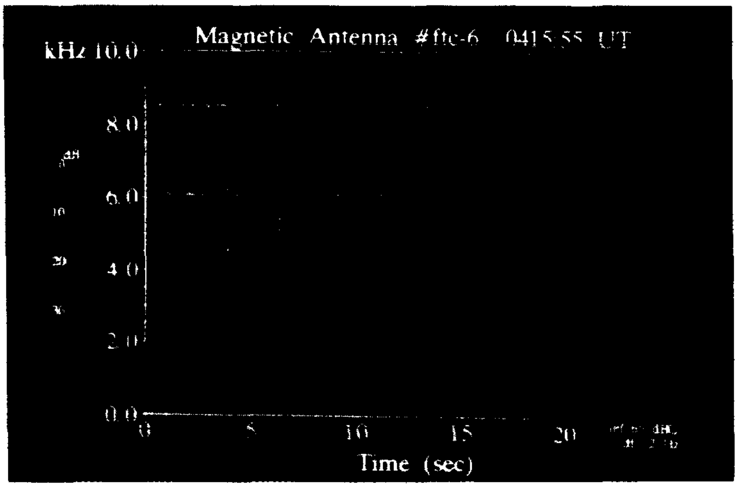

Fig. 2. The magnetic field in the frequency range 0-10 kHz as function of time. The perpendicular distance to the beam is 135 m and the parallel distance to the shuttle is 165 m.

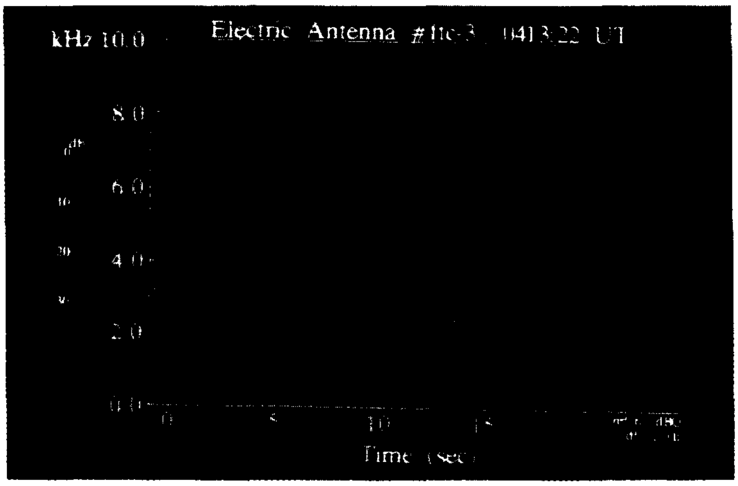

Fig. 3. The electric field in the frequency range 0-10 kHz as function of time. The perpendicular distance to the beam is 95 m and the parallel distance to the shuttle is 205 m.

absorbed in the plasma). For the experimental conditions encountered during the pulsed flux-tube connection, the model predicts the magnetic field vector **B** to be polarized in a plane with the normal of the plane having the angle $\theta_k = 60^o$ to the earths magnetic field and an azimuth angle $\alpha_k = -11^o$ (for $\alpha_k = 0^o$ the normal lies in the plane containing the beam and the PDP).

With calibrated wave receiver measurements /5/ and with the complete information on the PDP and shuttle attitudes, the magnetic field components required for the field to be polarized in this plane, *and* to be consistent with the measured spin modulation has been found. The amplitude of the three magnetic components are shown in Figure 5 as function of perpendicular distance to the beam (white markers) for the three magnetic antenna periods (see Figure 1). The components are given in a cylindrical coordinate system with the magnetic field line passing through the FPEG as the cylinder axis, and ρ as the radial component, ψ as the azimuthal component, and z as the axial component. Also shown is the amplitude of the three components predicted by the model (black markers).

The lower hybrid frequency, f_{LHR}, for the experiment was about 3 kHz, and thus the first harmonic of the 1.22 kHz pulsing frequency was below f_{LHR}, while the third and higher harmonics were at frequencies above f_{LHR}. Below f_{LHR}, Cherenkov resonance gives rise to one evanescent and one propagating wave, corresponding to a root 1 and root 2 respectively of the dispersion relation. Above f_{LHR}, root 1 becomes real and corresponds to resonance with waves at the Whistler-mode resonance cone. In general, root 1 gives several order of magnitude larger contributions to the wave-fields than root 2, however, below f_{LHR} the fields are strongly damped with radial distance due to their evanescent nature, and become smaller than the root 2 fields at a radial distance of about 40 m. At higher harmonic frequencies observations continue to compare well with root 2 fields, but are orders of magnitude below the fields arising from root 1. The apparent lack of field contributions generated at the Whistler-mode resonance cone is at present not understood.

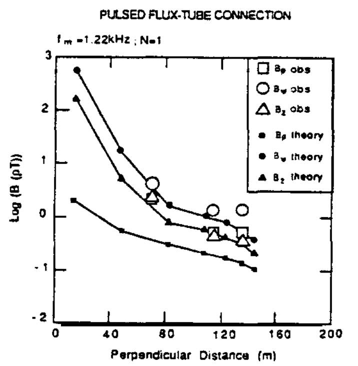

Fig. 5. Observed and predicted amplitudes of the three magnetic field components.

While observations and predictions of the amplitude of the magnetic components are in good agreement for the first harmonic, their phase relationship does not agree very well. The observed magnetic field is largely linearly polarized, provided it lies in the plane given by the model, however, the model field is mostly circularly polarized. To illustrate this discrepancy we show in Figure 6 the magnetic elliptical polarization in the spin-plane of the observed and of the predicted field. (Note that a magnetic field elliptically polarized in the spin plane in general will give rise to an observed field of the shape shown in Figure 4. The search coil gives a measure of the maximum amplitude of the field projected onto the axis of the search coil.) The model field polarization differs significantly from the measured one. This leads us to the conclusion that while the amplitude of the general disturbance generated at the fundamental of the pulsing frequency is comparable to the one predicted by /6,8/ the current system stimulating the field differs significantly to the one assumed in the model, namely a helical current formed by the spiraling motion around the earth's magnetic field of the beam electrons. We consider at least two other sources of radiation as important: one is the return current to the spacecraft, and the other is the turbulent wake formed behind the beam by the motion of the shuttle (7.8 km/s). While the PDP reached a distance perpendicular to the beam of 165 m during the pulsed beam sequence, the PDP was never more than 30 m from the beam wake.

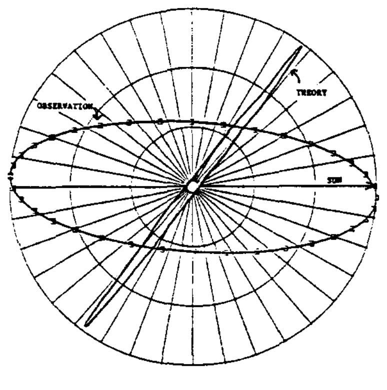

Fig. 6. Polarization in the PDP spin-plane of the observed and of the predicted first harmonic magnetic field component.

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