Radio Pumping of Ionospheric Plasma with Orbital Angular Momentum

T. B. Leyser,[1,*] L. Norin,[2] M. McCarrick,[3] T. R. Pedersen,[4] and B. Gustavsson[5]

[1]*Swedish Institute of Space Physics, Box 537, SE-751 21 Uppsala, Sweden*
[2]*Department of Physics and Astronomy, Uppsala University, Box 515, Uppsala SE-751 20, Sweden*
[3]*BAE SYSTEMS Advanced Technologies, 1250 24th St, NW, Suite 850, Washington, D.C., USA*
[4]*Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts 01731, USA*
[5]*Department of Physics and Technology, University of Tromsø, N-9037 Tromsø, Norway*
(Received 8 October 2008; published 12 February 2009)

Experimental results are presented of pumping ionospheric plasma with a radio wave carrying orbital angular momentum (OAM), using the High Frequency Active Auroral Research Program (HAARP) facility in Alaska. Optical emissions from the pumped plasma turbulence exhibit the characteristic ring-shaped morphology when the pump beam carries OAM. Features of stimulated electromagnetic emissions (SEE) that are attributed to cascading Langmuir turbulence are well developed for a regular beam but are significantly weaker for a ring-shaped OAM beam in which case upper hybrid turbulence dominates the SEE.

DOI: 10.1103/PhysRevLett.102.065004 PACS numbers: 94.20.Tt, 52.25.Os, 52.40.−w, 95.85.Bh

High-frequency (HF) electromagnetic waves beamed into the ionosphere may excite complex plasma turbulence involving a wide range of interacting temporal and spatial scales. The HF pumped turbulence depends, among a number of parameters, on the energy and momentum of the pump field. The momentum of the electromagnetic field has contributions from both a linear part and an angular part. The latter in turn is made up from the polarization, which depends on the photon spin, and the orbital angular momentum (OAM), which depends on the spatial distribution of the electromagnetic field. Whereas the polarization is a well-known feature of radio waves the OAM is a relatively unexplored property at radio frequencies. Here we demonstrate experimentally the formation of a radio beam with a helical wave front carrying OAM and present the first results from using such a beam to pump ionospheric plasma. The experiments were performed in February 2008 at the High frequency Active Auroral Research Program (HAARP) near Gakona in Alaska, USA.

OAM has been studied extensively at optical frequencies [1]. Well-defined OAM has been identified in beams of laser light with a Laguerre-Gaussian amplitude distribution in paraxial approximation theory [2]. Transfer of OAM carried by ring-shaped laser beams to absorptive particles has been observed in experiments [3]. The effects of photon OAM interacting with atmospheric turbulence has been studied theoretically with respect to optical communication [4].

More recently, OAM has also been considered in the radio domain. According to theory the ponderomotive force exerted by an electromagnetic field on a plasma has a contribution from the OAM of the field [5]. Numerical modeling has shown that a ring-shaped radio beam may carry OAM and that it is possible to form such a beam with an antenna array consisting of a limited number of transmitters on the ground [6]. It was emphasized that in the radio domain vector field quantities can be measured and transmitted directly, in contrast to the case at infrared and optical frequencies at which first order field quantities can currently not be detected directly.

In the present experiments the radio beam was formed with the HAARP phased array antenna, in which the phase and amplitude of the field is controlled individually in each antenna element. The array antenna consists of 180 crossed dipoles arranged in a rectangular planar 12×15 array. A radio beam with a spiral wave front carrying OAM was obtained by imposing an $l\varphi$ dependence of the phase of the pump field in a plane perpendicular to the beam axis, where l is an integer and φ is the azimuthal angle. The OAM is approximately proportional to the array phasing factor l. The maximum OAM transmitted (at $l = \pm 3$) was limited by the coupling between neighboring antenna elements. At $l = \pm 3$, six transmitters (out of 360) in the center of the array were turned off to avoid too high antenna coupling. The polarization was always circular ordinary mode, independent of l.

The pumped plasma turbulence was diagnosed by receiving on the ground electromagnetic emissions at HF and optical frequencies, however, only by measuring the power but not the OAM content in the received signals. Stimulated electromagnetic emissions (SEE) at frequencies near f_0 [7] were detected in Gakona. The SEE was sampled with a Hewlett-Packard E1437A 20 megasamples/s, analog-to-digital converter connected to a wide band HF dipole antenna. Optical emissions from the turbulence were detected with several imagers on the ground.

Figure 1 displays the HAARP antenna beam for $f_0 = 2.85$ MHz with $l = 0$ (left) and $l = +1$ (right). For $l = 0$ the beam has maximum intensity in the center while for $l = +1$ the beam power distribution is ring-shaped. The characteristic power minimum in the center of the beam for $l \neq 0$ is due to the phase ambiguity of the field in the

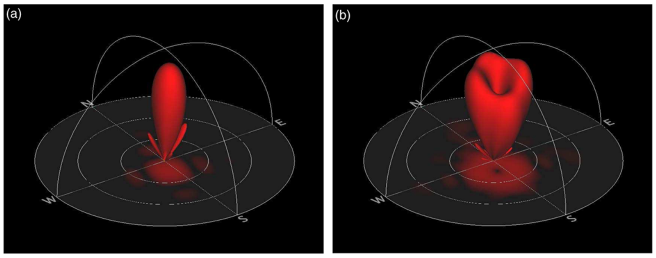

FIG. 1 (color online). HAARP antenna beam for $l = 0$ (left) and $l = +1$ (right) at $f_0 = 2.85$ MHz. The beam is in the geomagnetic zenith direction and the polarization is ordinary mode. The pattern was calculated using measured currents on the 360 dipole antennas during operation at 10 kW per transmitter.

center. The peaks in the main lobe for $l = +1$ are due to the rectangular shape of the antenna array. Also seen in Fig. 1 are the strongly suppressed side lobes. Because the beam is much wider for $l \neq 0$ than for $l = 0$ the effective radiated power (ERP) is considerably lower for $l \neq 0$.

Figure 2 shows images of pump-induced optical emissions at 5577 Å (the Oxygen green line) for $f_0 = 2.85$ MHz, detected by the HAARP all sky imager. The pump was cycled 4 min with $l = 0$ and 4 min with $l = +1$, starting at 04:20:00 UT (LT = UT − 9 hours). The HAARP beam was in the geomagnetic zenith direction which gives maximum optical emissions [8]. The luminescence results from collisional impact of energized electrons on neutral atmospheric constituents, the electrons being accelerated in the pumped plasma turbulence. The images in Fig. 2 are for $l = 0$ at 04:29:15 UT (left) and for $l = +1$ at 04:32:15 UT (middle) and 04:35:15 UT (right). For $l = 0$ a bright central spot of enhanced emissions is seen. The peak brightness is about 110 rayleigh (R), well above the background level of 45–50 R. The full-width at half-maximum of the emission region is about 10°. Surrounding the central spot is a darker region and at about 10° from geomagnetic zenith a faint ring can be seen, despite the fact that the pump beam has a Gaussian shape.

The two images for $l = +1$ in Fig. 2 (middle and right) are from the same pump period and show an interesting temporal evolution. Both images exhibit an intensity minimum in the center of the emission region, consistent with the zero intensity of the pump beam in the center for $l \neq 0$. Shortly after pump-on, two roughly ring-shaped and concentric emission regions can be seen (middle image). The bright central spot for $l = 0$ is replaced by a small ring-shaped region. In the image obtained 3 min later the smaller ring cannot be seen any longer and only the larger ring remains (right image). In this steady state the ring-shaped emission region is consistent with the ring-shaped pump beam for $l = +1$ with its intensity minimum in the center.

The width of the optical emission region at $l = 0$ of about 10° is smaller than the −3-dB pump beam width of 15° at $f_0 = 2.85$ MHz, as seen from the dashed curve in the left image in Fig. 2 which shows the −3 dB contour of the pump beam power. Further, the edges of the bright central spot for $l = 0$ are significantly sharper than expected for a Gaussian pump beam. We interpret these results by that the pump beam has undergone self-focusing, in which significant concentration of the emission region into a smaller and brighter spot occurs during pumping. Such self-focusing is commonly observed at HAARP for $f_0 = 2.85$ MHz within typically less than 1 min of continuous wave pumping [9]. However, in the present experiments the temporal development of the self-focusing after the first pump-on for $l = 0$ was not observed because of the too bright background sky near sunset in the early part of the experiment.

Self-focusing of the pump beam is also consistent with the presence of the inner ring in the middle image in Fig. 2 for $l = +1$. The pump beam with $l = 0$ creates a cavity during self-focusing with an angular extent given approximately by that of the optical emission region in the left image of Fig. 2. As the pump beam is switched from Gaussian ($l = 0$) to helical ($l = +1$) the central cavity slowly decays because of the minimum pump power in

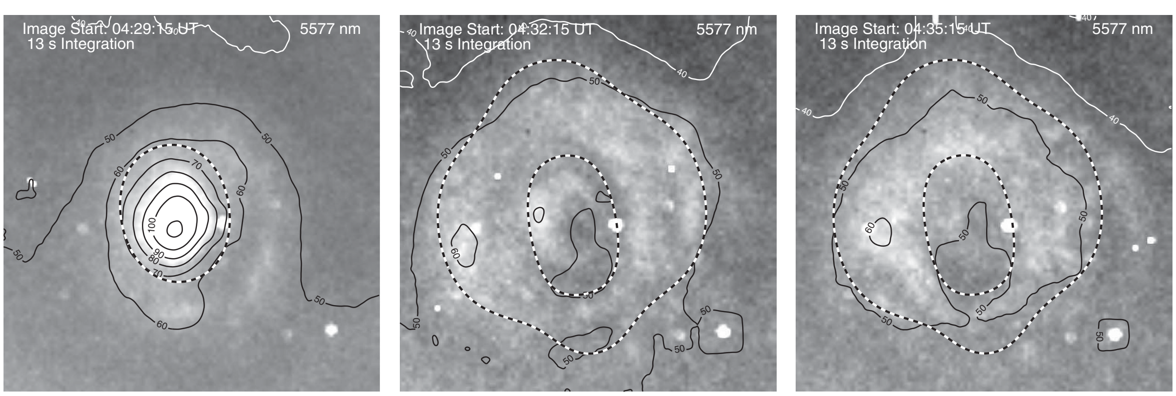

FIG. 2. Images of pump-induced optical emissions at 5577 Å for $f_0 = 2.85$ MHz (27 February 2008), for $l = 0$ at 04:29:15 UT (left) and for $l = +1$ at 04:32:15 UT (middle) and 04:35:15 UT (right). The pump beam was directed in geomagnetic zenith, 14° off zenith at 202° azimuth. The dashed curves are the −3-dB contours of the pump beam power.

the beam center for $l = +1$ which cannot sustain the cavity. The decaying cavity thus partially focuses the helical beam into the inner ring seen in the middle image in Fig. 2. As the cavity slowly decays, so does the inner ring, leaving only the ring-shaped region from the not focused beam with $l = +1$ (right image). The outer ring in the middle image and the remaining ring in the right image fit nicely within the -3-dB contours of the ring-shaped pump beam shown as dashed curves in Fig. 2.

Ring-shaped luminescence regions have been observed also for regular ($l = 0$) pump beams in experiments at the EISCAT-Heating (European Incoherent Scatter association) facility in Norway for f_0 near the fourth electron gyro harmonic [10] and have also been observed at HAARP for f_0 near the second gyro harmonic. We tentatively attribute those results to the theoretical predictions of Istomin and Leyser [11] which show that electron acceleration by localized upper hybrid oscillations is the strongest where the pump field is the most inhomogeneous, i.e., on the circular pump beam edge.

Figure 3 displays two overlaid SEE spectra for $f_0 =$ 4.50 MHz with $l = 0$ (blue) and $l = +1$ (red). The pump was cycled 30 s with $l = 0$, 30 s off, 30 s with $l = +1$, and 30 s off, which was repeated for 14 or 16 min. A narrow continuum maximum (NCM) [12] downshifted by 2 kHz from f_0 is seen reaching more than 40 dB above the background noise level. The NCM sits on a narrow continuum (NC) which extends about 40 kHz below f_0. At 6–9 kHz below f_0 is a split downshifted maximum (DM) feature [13] and about 6 kHz above f_0 is an upshifted maximum (UM), however, only exhibiting a single peak. The mirror frequency of the UM coincides with the peak of the split DM which occurs at the higher frequency. Further, there are systematic differences in the SEE for $l = 0$ and $l \neq 0$. As seen in Fig. 3, the NCM feature is about 3 dB stronger for $l = 0$ than for $l = +1$. In the upper sideband the SEE is 1–2 dB stronger for $l = +1$.

Figure 4 shows SEE spectra for $l = 0$ (blue) and $l = +3$ (red). Again the most prominent spectral feature is the NCM which reaches more than 40 dB above the background noise level, but now only for $l = 0$. The SEE intensity at the same frequency downshift for $l = +3$ is about 20 dB lower. Similar to the case in Fig. 3 for $l = +1$, the SEE is 1–2 dB stronger in the upper sideband for $l = +3$ than for $l = 0$. However, for smaller upshifts, between f_0 and the UM, the SEE intensity is higher for $l = 0$ similar to the situation at small downshifted frequencies. The SEE for $l = -n$ is similar to that for $l = +n$. Also, for $l = \pm 2$ the difference in the SEE spectrum compared to $l = 0$ is larger than that for $l = \pm 1$ but smaller than that for $l = \pm 3$.

The NCM and the associated NC have been attributed to cascading Langmuir turbulence excited just below the pump reflection height [12], where the electric field of the vertically transmitted pump wave undergoes swelling and is nearly parallel to the ambient geomagnetic field. The DM and UM features, on the other hand, are attributed to upper hybrid turbulence, excited typically a few kilometers below the pump reflection height where the pump electric field is essentially perpendicular to the geomagnetic field [7]. Thus, the SEE spectral features that are stronger for $l = 0$ than for $l \neq 0$ (Figs. 3 and 4) are those attributed to Langmuir turbulence. Further, since in these experiments we could not detect any difference in the SEE for $l = \pm n$ we conclude that the SEE did not depend on the OAM of the pump beam, but only on the spatial distribution of the pump beam power. Further, with ordinary mode circular polarization the total angular momentum of the pump field is larger for $l = -n$ than for $l = +n$. This asymmetry was neither detected in the SEE. Therefore, the detection of explicit OAM effects in the plasma, rather than dependencies on the power distribution in the pump beam, remains an interesting open problem.

For the magnetized ionospheric plasma all pump rays that propagate within the critical (Spitze) angle of about 7°

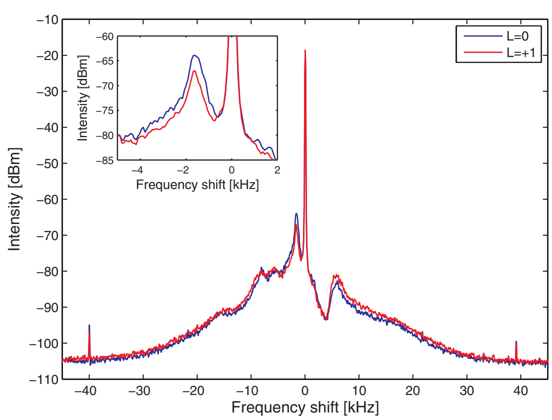

FIG. 3 (color online). SEE spectra at ±45 kHz around $f_0 =$ 4.50 MHz with $l = 0$ (blue, 20:16:15 UT) and $l = +1$ (red, 20:17:15 UT), for a vertical pump beam (24 February 2008). The magnified part shows the SEE from $f_0 - 5$ kHz to $f_0 + 2$ kHz. The ERP was 1.05 GW for $l = 0$ and 331 MW for $l = +1$.

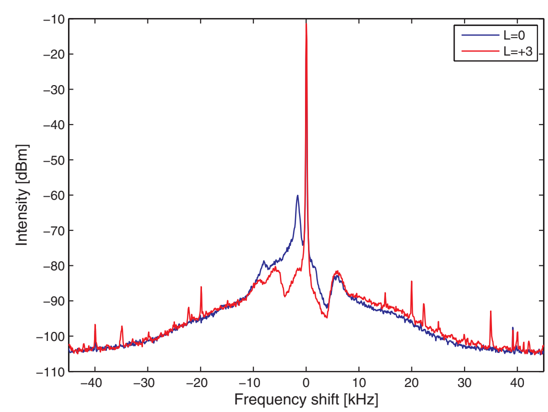

FIG. 4 (color online). SEE spectra at ±45 kHz around $f_0 =$ 4.50 MHz with $l = 0$ (blue, 20:22:15 UT) and $l = +3$ (red, 20:23:15 UT), for a vertical pump beam (25 February 2008). The ERP was 1.05 GW for $l = 0$ and 132 MW for $l = +3$.

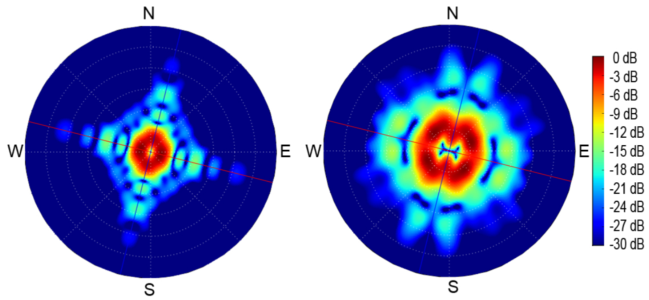

FIG. 5 (color online). Horizontal cross section of HAARP antenna radiation pattern for $l = +1$ (left) and $l = +3$ (right) for a vertical beam at $f_0 = 4.50$ MHz. The pattern appears tilted since the antenna array is oriented 14° east of north. The peaks in the ring patterns are due to the rectangular shape of the array.

from the vertical at HAARP reach the plasma resonance where the local plasma frequency equals f_0. These rays efficiently excite Langmuir turbulence. However, for $l \neq 0$ the cross section of the pump beam is ring shaped so that for a vertical beam (applying to Figs. 3 and 4) the near vertical rays are very weak and thus Langmuir turbulence is correspondingly weak too. On the other hand, for $l = 0$ the intensity is maximum for the vertical rays. This explains the stronger NCM for $l = 0$ than for $l \neq 0$. Further, the angular width of the intensity minimum in the center of the pump beam for $l \neq 0$ is wider for larger $|l|$, as illustrated in the computed pump beam cross sections in Fig. 5 for $l = +1$ (left) and $l = +3$ (right). This implies that the rays that reach the plasma resonance are weaker for larger $|l|$, which is consistent with the weaker NCM for larger $|l|$ (Figs. 3 and 4).

The NCM feature has never been observed to be as strong as in these experiments at HAARP. This is attributed to the high ERP of about 1 GW obtained for $l = 0$. The previous experiments in which the NCM was identified were performed at the Sura facility in Russia with an ERP of 80–180 MW [12,14]. The NCM was only detected for f_0 sufficiently close to an harmonic of the ionospheric electron gyro frequency at which the excitation of upper hybrid turbulence is suppressed. At other f_0 the NCM could be identified shortly after pump-on, before the slower growing upper hybrid related features had become sufficiently strong. In Figs. 3 and 4, $f_0 = 4.50$ MHz which is not near an electron gyro harmonic. The ERP in the experiments at HAARP is apparently sufficiently high to excite both Langmuir and upper hybrid turbulence at the same time (for $l = 0$).

The present experiments have demonstrated the transmission of radio beams carrying OAM into the ionosphere. The luminescence from the pumped plasma turbulence is consistent with the ring-shaped power distribution of the pump beam. The dependence of the SEE on the OAM of the pump beam is also interpreted in terms of the power distribution in the beam, rather than the actual OAM carried by the beam. Thus, the detection of explicit OAM effects in the pumped plasma remains an interesting topic for future experiments. Finally, OAM beams may provide new means to investigate and interact with plasma vortices, e.g., in aurora. Also, OAM modulation could significantly increase the information that can be transmitted by radio beams, independent of the amplitude (AM) and frequency modulation (FM).

We gratefully acknowledge Ralph Wuerker for additional experimental data, Lennart Åhlén, Paul Bernhardt, Craig Selcher, and the HAARP staff for support, and Tobia Carozzi for comments on the manuscript. This research was supported by the Swedish Research Council. Work at AFRL was conducted under AFOSR task 2311AS. HAARP is a Department of Defense project operated jointly by the U. S. Air Force and U. S. Navy.

*thomas.leyser@irfu.se

[1] G. Molina-Terriza, J. P. Torres, and L. Torner, Nature Phys. **3**, 305 (2007).
[2] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Phys. Rev. A **45**, 8185 (1992).
[3] H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop, Phys. Rev. Lett. **75**, 826 (1995).
[4] C. Paterson, Phys. Rev. Lett. **94**, 153901 (2005).
[5] Y. N. Istomin, Phys. Lett. A **299**, 248 (2002).
[6] B. Thidé, H. Then, J. Sjöholm, K. Palmer, J. Bergman, T. D. Carozzi, Y. N. Istomin, N. H. Ibragimov, and R. Khamitova, Phys. Rev. Lett. **99**, 087701 (2007).
[7] T. B. Leyser, Space Sci. Rev. **98**, 223 (2001).
[8] T. R. Pedersen, M. McCarrick, E. Gerken, C. Selcher, D. Sentman, H. C. Carlson, and A. Gurevich, Geophys. Res. Lett. **30**, 1169 (2003).
[9] M. J. Kosch, T. Pedersen, E. Mishin, M. Starks, E. Gerken-Kendall, D. Sentman, S. Oyama, and B. Watkins, J. Geophys. Res. **112**, A08 304 (2007).
[10] M. J. Kosch, M. T. Rietveld, A. Senior, I. W. McCrea, A. J. Kavanagh, B. Isham, and F. Honary, Geophys. Res. Lett. **31**, L12 805 (2004).
[11] Y. N. Istomin and T. B. Leyser, Phys. Plasmas **10**, 2962 (2003).
[12] B. Thidé, E. N. Sergeev, S. M. Grach, T. B. Leyser, and T. D. Carozzi, Phys. Rev. Lett. **95**, 255002 (2005).
[13] T. B. Leyser, B. Thidé, H. Derblom, Å. Hedberg, B. Lundborg, P. Stubbe, and H. Kopka, J. Geophys. Res. **95**, 17 233 (1990).
[14] P. V. Kotov, L. Norin, E. N. Sergeev, S. M. Grach, and B. Thidé, Adv. Space Res. **40**, 377 (2007).