Stimulated Electromagnetic Emission in a Magnetized Plasma: A New Symmetric Spectral Feature

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Observations of a new type of stimulated electromagnetic emission, excited by a powerful hf electromagnetic wave in the plasma of the ionosphere, are reported. The new feature, called broad symmetrical structure, consists of two spectral maxima, symmetrically located around the pump frequency f_0, at offset frequencies of 15 to 30 kHz.

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It is well known from laser plasma experiments and theory that a powerful electromagnetic wave (with frequency f_0), incident upon a plasma, may generate electromagnetic waves at the frequencies nf_0, $f_0/2$, and $3f_0/2$.[1] Secondary waves of this type were also observed in ionospheric modification experiments at Tromsø.[2] However, much stronger secondary electromagnetic waves were detected in these experiments at frequencies approximately ranging from $0.98f_0$ to $1.04f_0$. This type of sideband radiation has been termed stimulated electromagnetic emission (SEE).[3] First experimental SEE results were reported by Thidé, Kopka, and Stubbe,[4] and a classification of the main SEE characteristics was given by Stubbe *et al.*[5]

Ionospheric modification experiments may be grouped into active geophysical experiments and general plasma physics experiments. In the latter case, "ionosphere" is to be understood as a magnetized plasma with a high degree of spatial and temporal homogeneity, as measured by the length and time scales of the processes involved. SEE experiments belong to this second category. An especially interesting aspect of these experiments is the fact that the range of available pump frequencies encompasses some of the low-order electron cyclotron harmonics, $f_0 \approx nf_L$ ($n=3,4,5,6$), with $f_L \approx 1.35$ MHz. Our experiments have shown that certain SEE features depend very sensitively upon $f_0 - nf_L$ when $f_0 \approx nf_L$.[6] The new results presented below possess this property, too.

The major SEE features observed in previous experiments are the so-called continuum, the down-shifted maximum (DM), the broad up-shifted maximum (BUM), and the down-shifted peak (DP).

The continuum is a continuous spectrum appearing on both sides of f_0, with a peak at f_0. The continuum is usually asymmetric, with more energy on the down-shifted side. The width of the down-shifted portion of the continuum is strongly variable, ranging from a few kHz up to as much as 100 kHz. The DM is a spectral maximum occurring at a frequency offset from the pump approximately given by $\Delta f_{\rm DM} = -2\times10^{-3} f_0$, with a width of a few kHz.[5] Like the continuum, the DM has a highly variable shape. In one extreme, the DM appears as a slightly elevated portion within a broad down-shifted continuum. In the other extreme, the DM is sharply peaked, looking like the copy of an equally sharp continuum (see Fig. 2 below). The DM is often accompanied by a considerably weaker up-shifted maximum (UM) at or close to the mirror frequency of the DM (see Figs. 1 and 2).

Whereas the continuum and the DM have been observed for all pump frequencies used so far, the BUM and the DP are restricted to the case that f_0 is close to a cyclotron harmonic, $f_0 \approx nf_L$. The BUM is a feature that exists exclusively on the up-shifted side and may reach out to $\Delta f = 200$ kHz, or even more. The peak frequency depends strongly on f_0 and can be approximated by $\Delta f_{\rm BUM} = f_0 - nf_L$.[6] When f_0 is lowered so that $\Delta f_{\rm BUM}$ approaches zero, the BUM disappears. The lowest values for $\Delta f_{\rm BUM}$ were found to be 15 kHz. The DP is a sharp peak approximately 2 kHz below f_0 (see Fig. 3). For $f_0 \approx 3f_L$, the DP has been found to be a

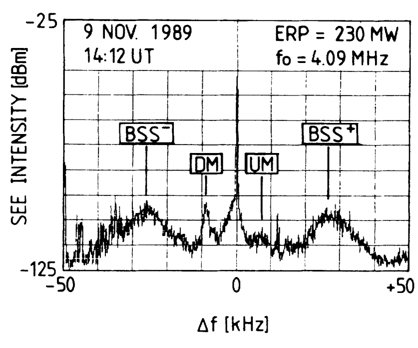

FIG. 1. SEE spectrum, recorded on 9 November 1989 at 14:12 UT, at a location 15 km from the Tromsø heating facility, using a HP 3585A spectrum analyzer connected to a delta antenna with 12.5 m height and 15 m base length. The abscissa shows Δf, the frequency offset from the pump frequency f_0 ($f_0 = 4.09$ MHz). The ordinate gives the spectral intensity in dBm on a 10 dB/div scale. The pump wave was in the ordinary mode, and the effective radiated power (product of transmitted power and antenna gain) was 230 MW. In addition to the well-known DM and UM features, two pronounced spectral maxima with peaks at $\Delta f \approx \pm 27$ kHz are labeled $\rm BSS^+$ and $\rm BSS^-$. The spike at 12 kHz as well as other sharp spikes (especially below -33 kHz) are due to interfering broadcasting stations.

very strong feature. However, only weak signs of a DP have been seen for $n=4$ and 5, and none for $n=6$, despite systematic searches.

Stimulated electromagnetic emission has been a major research subject during the past years, not only at Tromsø, but also at other ionospheric modification facilities.[7-9] A new type of stimulated electromagnetic emission was discovered in experiments performed at Tromsø in November 1989, consisting of a pair of broad maxima, symmetrically located around f_0 at $|\Delta f| \approx 15$–30 kHz. An example of this, as we will call it, broad symmetrical structure (BSS) is shown in Fig. 1. In this figure, the down-shifted BSS maximum is marked by BSS^-, and the up-shifted maximum by BSS^+. We see that the BSS is a very distinctly developed feature, comparable in strength to the usually dominating DM.

The spectral shape of the BSS^+ bears some resemblance with the BUM, and the question arose whether these two features are physically related. If they were, the BSS^+ should show the characteristic dependence on f_0 that has been well documented for the BUM; i.e., the BSS^+ should move to higher frequencies Δf, while simultaneously fading away, when f_0 is increased. Corresponding experiments were performed, and characteristic results are shown in Fig. 2. Starting at Fig. 2(a), where a BSS is not identifiable, and going to higher pump frequencies, we see that a BSS develops at $|\Delta f_{BSS}| \approx 15$ kHz, grows in strength, settles at $|\Delta f_{BSS}| \approx 30$ kHz, and eventually disappears in place without further frequency change. This frequency dependence differs greatly from the frequency dependence known for the BUM. It is thus beyond doubt that the BSS and the BUM are independent features. They have in common, however, that they do not exist for $|\Delta f|$ below 15 kHz. We see from Fig. 2 that the BSS is excited only in a very narrow pump frequency range of about $\Delta f_0 \approx 40$ kHz, corresponding to 1% of f_0.

It should be noted that the pump frequencies used in these experiments were close to the triple electron gyrofrequency, $f_0 \approx 3f_L$. Attempts to find the BSS at other frequencies, particularly at $f_0 \approx nf_L$, with $n=4$, 5, and 6, were unsuccessful. In this regard, there exists a similarity between the BSS and the DP. Despite this similarity, the DP has never been found to coexist with the BSS. There are clear indications in our data that the BSS occurs at pump frequencies slightly above the pump frequency range in which the DP exists. This is demonstrated in Fig. 3. In the upper two panels, relating to $f_0=4.04$ MHz, we see a well developed DP, but no sign of a BSS or DM. In the lower two panels, for a pump frequency increased by only 40 kHz (or 1% of f_0), the DP is absent, but a pronounced BSS and DM have appeared. This is one more example of the puzzling com-

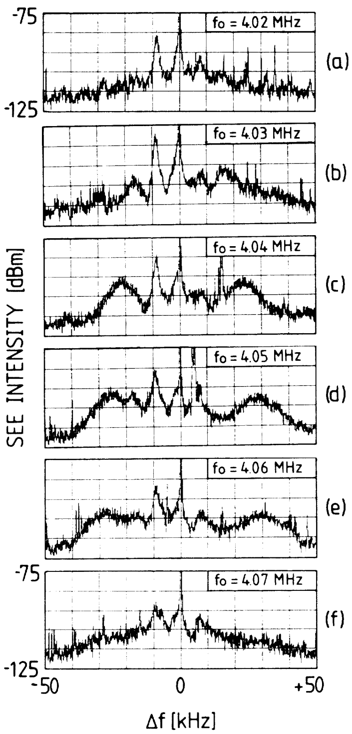

FIG. 2. SEE spectra, recorded on 9 November 1989 between 15:02 and 15:58 UT, for six pump frequencies f_0 ranging from 4.02 to 4.07 MHz. All spectra show the DM and UM, and spectra (b)-(e) show the BSS^- and BSS^+ maxima. The intermediate maximum at -18 kHz in (d), also visible in (e), is the signature of the 2DM (Ref. 5). The disturbances at 15 kHz in (c) and 5 kHz in (d), as well as other spiky disturbances, are due to broadcasting stations. Further text as in Fig. 1.

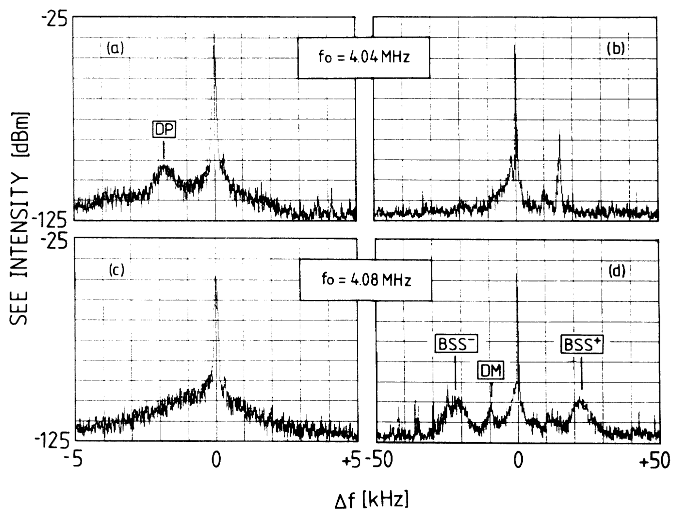

FIG. 3. SEE spectra, recorded on 9 November 1989 between 13:42 and 14:00 UT, for two different pump frequencies [(a),(b): 4.04 MHz; (c),(d): 4.08 MHz] and two different frequency scales [(a),(c): 1 kHz/div; (b),(d): 10 kHz/div]. The strong peak at 15 kHz in (b) as well as other sharp spikes are due to interfering broadcasting stations. Further text as in Fig. 1.

plexity and multiplicity of SEE spectra and their extreme dependence on $f_0 - nf_L$ when $f_0 \approx nf_L$.

The experimental parameters that can be controlled in ionospheric SEE observations are the frequency, power, polarization, and beam direction of the pump wave. The important parameter f_L is set by external conditions. The value of f_L in the SEE excitation region is subject to regular variations, due to changes of the altitude of the excitation region. In particular, the excitation region moves to higher altitudes (and, correspondingly, f_L changes to lower values) in the late afternoon hours. It was observed during these times that the pump frequency range of BSS existence moved to lower frequencies. This finding gives further support to our conjecture that the BSS excitation (like the BUM and DP excitation) requires f_0 to fall into a narrow frequency range near nf_L.

The BSS has been a strong and repetitive feature in the November 1989 experiments. It may appear surprising, therefore, that the BSS has not shown its existence in previous experiments. The narrowness of the pump frequency range in which the BSS exists, and the dependence of the position of this frequency range on f_L (i.e., on the altitude of the excitation region), offer the likely explanation. The ionospheric conditions during November 1989 were markedly different from those encountered in previous experiments, due to a strongly enhanced solar activity level, corresponding to a higher ionosphere or lower values of f_L. We conjecture, therefore, that the frequency range of BSS existence lay outside the range of pump frequencies used in the previous experiments.

In summary, we have found a new SEE feature, called broad symmetrical structure. The BSS consists of two maxima in the lower and upper sidebands, symmetric around the pump frequency f_0, with offset frequencies $|\Delta f_{BSS}|$ in the range 15 to 30 kHz. The BSS has only been observed for pump frequencies falling into a $\sim$40-kHz interval near $3f_L$. Further attempts to find the BSS at other cyclotron harmonics appear necessary. The BSS is the third SEE feature, after the DP and BUM, that occurs only if f_0 is close to a cyclotron harmonic. The BSS has the narrowest pump frequency range of existence and is the only SEE feature that is almost perfectly symmetric around f_0. Putting all the observed SEE features together, one finds a highly complex phenomenon which constitutes a serious challenge to our understanding of nonlinear-wave-induced processes in a magnetized plasma.

The theoretical understanding of the SEE phenomenon reached up to date is still at a rather moderate level. There is general agreement that the basic mechanism involved in the generation of secondary electromagnetic waves is mode converting scattering of high-frequency electrostatic waves at low- or zero-frequency density perturbations.[4,5] These, in turn, are generated by the primary electromagnetic wave (the pump) via parametric processes. Since the experimental technique used in SEE observations, unlike the incoherent-scatter technique, is in no way wave-number selective, it is not even clear from the beginning that the SEE spectra should possess maxima at all. It has been proposed[5] that the spectrum maximizes at those frequencies which have the largest spatial range of generation. By applying this criterion to the SEE caused by Langmuir and ion-acoustic waves as excited by the conventional parametric-decay instability at small angles with respect to the magnetic field, a great number of observational details, including the dependence of Δf_{DM} on f_0, have been explained.[5] However, this approach is limited to those SEE features which do not depend on f_0 being close to nf_L.

Considering cyclotron harmonics effects, it is clear that neither the ion dynamics nor the pump-wave properties are affected in any noticeable way by f_0 approaching nf_L $(n > 1)$. It is thus a necessary conclusion that the high-frequency electrostatic waves have to play the key role in cyclotron harmonics effects. This points most naturally to electron Bernstein modes. One may also incorporate upper hybrid waves. This is because these waves attain a small group velocity as $f_0 \to nf_L$, which in turn means that they have a large residence time in the interaction region in this case.[6] Both of these wave types may be generated by a thermal resonance instability.[10,11] On the low-frequency side, lower hybrid waves should be taken into consideration, in addition to ion-acoustic waves and zero-frequency density perturbations. Lower hybrid waves may be generated by parametric decay of primary Bernstein–upper hybrid waves of frequency f_0 into secondary Bernstein–upper hybrid waves and lower hybrid waves. The BSS may then be understood as being due to scattering of primary Bernstein–upper hybrid waves by lower hybrid waves having the same or the opposite propagation direction. The secondary electromagnetic waves generated in this way would possess a spectrum which is symmetric around f_0, in agreement with observation. It is not obvious, however, that the proposed mechanism should reproduce the full set of observational properties, and it appears necessary, therefore, to await a quantitative analysis before firm conclusions regarding the physical nature of the BSS can be drawn.

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