ANOMALOUS BREMSSTRAHLUNG AND ANOMALOUS CYCLOTRON
EMISSION FROM PARTIALLY IONIZED GASES

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We have studied the radio-wave emissions from partially ionized plasmas in the frequency range from 1000 to 20 Mc/s and found that there appeared two kinds of anomalous emissions. The first (named the anomalous cyclotron emission) could be observed at the electron cyclotron frequency when the detecting frequency ω was above some critical frequency ω_{crit} .

The second (named the anomalous bremsstrahlung) was observed in the rather weaker external magnetic field when the detecting frequency ω was less than the

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critical frequency ω_{crit} . The experimentally observed characteristics of both anomalous emissions were very similar and would be explained by the same physical mechanism.

The emission spectrum reproduced in Fig. 1 was obtained as follows. The discharge tube of inner diameter 45 mm has a plane anode (40 mm in diameter) and a hot-cathode with a paraboloidal emitting surface of 30 mm in diameter. The anode and the cathode are placed 20 mm apart. Two probes are inserted radially in the midplane between the anode and the cathode. A radio wave emission from a plasma is picked up by these probes. The static magnetic field B uniform over the volume of the plasma to better than 0.2% is applied parallel to the axis of tube. The measurements of rf emission from a plasma are carried out by the radio interference field intensity meter (RI-FI meter). When a magnetic field is swept at constant discharge current I_d (keeping the detecting frequency at the fixed value) and the receiver output is continuously traced on the recorder, the emission spectrum is displayed.

As shown in the emission spectra of Fig. 1 (a), the extremely intense emission appears at the definite field intensity, corresponding to the respective detecting frequency. We can obtain the $f_b - f$ diagram by plotting the magnetic field intensity $f_b = \omega_b / 2\pi = eB / 2\pi m$, at which the resonant peak appears in the emission spectrum, as a function of detecting frequency f . Such a diagram is shown in Fig. 2. It is easily seen that the resonant peaks appear both at the cyclotron frequency $\omega = \omega_b$ and at its 2nd harmonic $\omega = 2\omega_b$. It is to be noted that a thermal noise power emitted by the plasma with the electron energy of a few eV cannot be detected, though the RI-FI meter used is the sensitive superheterodyne receiver. When the anomalous cyclotron emission is observed on the emission spectra, the output of IF amplifier of the RI-FI meter is seen on the synchroscope, as shown in the upper trace of Photos. 1 (a). The upper trace in Photo. 1 (a) are just straight line when there is no anomalous cyclotron emission. Therefore, this emission is not stationary, but is pulsive in time. The lower curve of Photo. 1 represents the low frequency oscillation of voltage between the cathode and the anode.

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It is remarked that the peaks at $\omega = \omega_b$ observed in Fig. 1 (a) are not those of the 'normal' cyclotron resonance and also that the peaks at $\omega = 2\omega_b$ are not those of the harmonics observed in a 'usual positive column', which were reported by several authors.⁽¹⁾ The anomalous 2nd harmonic results from the frequency-multiplying of the anomalous cyclotron emission, because it is shown experimentally that the latter emission can be frequency-mixed with a rf wave, fed from the external source. As the detecting frequency decreases further, the peak of anomalous cyclotron emission becomes smaller and disappears abruptly at some detecting frequency (critical frequency ω_{crit}). However, at a low frequency below ω_{crit} , there appears another intensive emission, which is not the anomalous cyclotron emission.

In the curve (1) of Fig. 1 (b), the resonant peak is the anomalous cyclotron emission for the detecting frequency near ω_{crit} . In the curve (2), the intense emission is observed in the low magnetic field range (from zero to about the cyclotron field). It is noted that, though the peak denoted by the sign @ seems to be that of the anomalous cyclotron emission, the peak

⑥ is not a resonant peak. The apparent feature of curve (2) changes with the variation of discharge parameters, such as a current I_d , an emissivity of cathode and a gas pressure, and the appearance of peak ⑥ depends on the case we have. The essential point is that for these low detecting frequency below ω_{crit} , the enormously intensive emissions appear in the low magnetic field region, including zero field. This intensive emission will be called the anomalous bremsstrahlung hereafter.

The anomalous bremsstrahlung is shown in the curve (3) of Fig. 1 (b), in which the apparent peaks and dips are seen. The emission pattern on the synchroscope at the peak of ① (at which $B = 0$) is shown in Phot. 1 (b), which shows that the anomalous bremsstrahlung is emitted pulsively. Such ① pulsed emission is seen at the dips of ② and ④ as well as at the peaks of ③ and ⑤. The received power above the zero level on the emission spectrum (curve (3)) is due to the anomalous bremsstrahlung. Meanwhile, the pulsed emission cannot be seen at the point ⑥.

The electron temperature T_e and the electron density

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n_e of the discharge plasma in the absence of an external magnetic field are measured by the usual Langmuir probe. The measured electron temperature of the xenon plasma at the pressure $p = 0.6$ Torr is $1.04 \sim 1.1 \times 10^4$ °K for the current range from 20 to 100 mA. There is a large Ramsauer effect in Xe gas⁽²⁾ and the collision probability with neutral particles is minimum at this electron energy (1 eV) and equal to about 5 cm^{-1} . Then the collision frequency ν and the mean free path ℓ of plasma electrons are estimated to be $\nu \approx 180 \text{ Mc/s}$ and $\ell \approx 0.33 \text{ cm}$ respectively, using the above numerical values. Since the electron density is measured to be $n_e \approx 2 \times 10^9 \text{ cm}^{-3}$ at $I_d \approx 50 \text{ mA}$ the plasma frequency is $f_p \approx 400 \text{ Mc/s}$. Therefore, under the above mentioned experimental conditions, $\omega \gtrsim \omega_p$, $\omega \gtrsim \nu$ and $\nu/\omega_p \approx 7.15 \times 10^{-2} \ll 1$.

The experimentally observed characteristics of both anomalous cyclotron emission and anomalous bremsstrahlung are very similar and summarized as follows: (1) The occurrence of both anomalous emissions depends on the kind of gas used. In our experiments, these

emissions are observed in Xe, Kr and Ar plasmas, but not observed in Ne and He plasmas. (2) These emissions are not stationary in time, but are emitted pulsively at a definite phase of the 1f oscillation in a dc discharge plasma. The pulsed emission occurs at the increasing phase as well as at the decreasing phase of the anode voltage when the detecting frequency or the plasma parameter is changed. (3) The emission intensity is enomously large and is of the same order for both anomalous emissions. It is more than 25 db in time average value above the thermal noise provided that the plasma electrons were in thermal equilibrium equivalent to 1 eV. Moreover, taking the correction of the duty cycle to these emissions, the peak power of the pulsed emission is more than 10 db above the time average value. (4) Both anomalous emissions depend sensitively on the state of discharge plasma. These emissions occur when a discharge current is rather small and a glow of discharge is seen on the anode surface or between the anode and the cathode. On the other hand, they do not occur when a glow contacts with the cathode surface. These emissions occur at the gas pressure range from 0.1 to 5 Torr.

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(5) The anomalous cyclotron emission occurs at $\omega = \omega_b$ when the detecting frequency ω is above ω_{crit} .

Its resonance line is surprisingly sharp and the width Δf is much less than the collision frequency

ν . ($\Delta f \lesssim 50$ Mc/s and $\nu \approx 200$ Mc/s). Moreover, this emission is observed even if ω is much less than ν . (6) The critical frequency is somewhat

smaller than ν , though ω_{crit} is varied in the range from 70 to 40 Mc/s with the plasma parameters. (7)

When the detecting frequency ω is less than ω_{crit} , the anomalous bremsstrahlung appears in the lower magnetic field region, including zero field. The region of the $f_b - f_b$ diagram, in which this emission is observed experimentally, is shown by the hatched one in Fig. 2.

The fact that Ramsauer effect is dominantly responsible for the excitation of these anomalous emissions suggests that these emissions may be resulted from the negative absorption effect in plasmas. The possibility of the negative absorption of radiation in plasma, had been studied theoretically by several authors.^(3~5) Previously we had reported⁽⁶⁾ the anomalous cyclotron emission at a microwave frequency in

9 and 4 Gc/s bands and discussed whether or not this emission may be interpreted as a phenomenon of negative absorption due to the cyclotron radiation.

Such an anomalous microwave emission was observed also by Coccoli.⁽⁷⁾ Recently, the negative absorption at $\omega = \omega_b$ was ascertained by Mitani et al..⁽⁸⁾

Now, if it can be considered that the anomalous cyclotron emission results from the effect of negative absorption due to the cyclotron radiation, we can interpret the anomalous bremsstrahlung as a phenomenon resulted from the negative absorption due to the bremsstrahlung and the above mentioned experimental results can be explained consistently.

Bekefi et al.⁽⁴⁾ have derived the following absorption coefficient for an arbitrary distribution of plasma electrons $f(v)$:

$$\alpha_{\omega} = -\frac{8\pi^3 c^2}{\omega^2} \int_0^{\infty} \eta_{\omega}(v) \frac{df}{du} 4\pi v^2 dv, \quad (1)$$

where, $u = mv^2/2$ and $\eta_{\omega}(v)$ is the rate at which the energy of frequency ω is emitted spontaneously by an electron with a velocity v . We can obtain α_{ω} in the presence of an external magnetic field by substi-

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tuting the emission rate $\eta_{\omega}(\nu)$ into Eq. (1). In the vicinity of the cyclotron frequency, $|\omega - \omega_b| \ll \nu(\nu)$, α_{ω} reduces to⁽⁵⁾

$$\alpha_{\omega} = \frac{4\pi}{3} \left(\frac{1 + \cos^2 \theta}{2} \right) \frac{\omega_p^2}{c} \int_0^{\infty} \frac{\partial}{\partial \nu} \left[\frac{\nu^3}{\nu(\nu)} \right] f(\nu) d\nu. \quad (2)$$

Similarly, α_{ω} in the absence of a magnetic field can be obtained. If the frequency ω is so small that the collision frequency $\nu(\nu)$ is predominant, $\omega \ll \nu(\nu)$, α_{ω} reduces to Eq. (2), in which 0 is taken as $\cos 0 = 1$. Therefore, at the low frequency, where $\omega \ll \nu(\nu)$, the absorption coefficient for bremsstrahlung is just the same as that for the cyclotron emission at $\omega = \omega_b$.

The followings are concluded by examining the absorption coefficient given by Eq. (2). If it is assumed that $\nu(\nu) \propto \nu^h$ (h being constant) and that all plasma electrons have the same energy (ν_0), then Eq. (2) reduces to $\alpha_{\omega} = (3 - h) \omega_p^2 / 3c \nu(\nu_0)$.

Accordingly, α_{ω} is negative if $h > 3$. If we assume the distribution function of the form, $f(\nu) \propto \nu^q \exp(-b\nu^2)$, then α_{ω} is negative if $q + 3 > h > 3$.

Therefore, the negative absorption can occur both at the low frequency region, where $\omega \ll \nu$ (due to the bremsstrahlung) and near the cyclotron frequency $\omega = \omega_b$ (due to the cyclotron radiation), when a departure of the distribution function of plasma electrons from the Maxwellian is appropriate and the gas used has the nature of $h > 3$. It can be shown that among rare gases, only Xe, Kr and Ar plasmas are expected to satisfy $h > 3$ in an appropriate electron energy range. From the standpoint of physical mechanism, there is no difference between the negative absorptions due to both radiations.

The above mentioned results just correspond to the experimental results. For the negative absorption due to the bremsstrahlung, the following conditions must be satisfied; $\omega \ll \nu$ and $\omega_b \ll \nu$ (including $\omega_b = 0$). Therefore, the region, in which the negative absorption effect occurs, is limited only in the neighbourhood of the origin of the f_b - f diagram. Actually, the anomalous bremsstrahlung is observed in the hatched region of Fig. 2 only. Since the negative absorption due to the bremsstrahlung occurs in the low frequency region, the negative absorption due to the

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cyclotron radiation may be masked in the low frequency region, even if the latter occurs. This fact may explain the existence of critical frequency ω_{crit} , though there is no theoretical limit on the frequency of negative absorption due to the cyclotron radiation. We may suppose that the pulsed character of the anomalous emissions results from the reason that a distribution of plasma electrons departs from the Maxwellian in the pulsed duration only. This fact will be examined further.

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List of Figure Captions

FIG. 1. Radio frequency emission (in relative unit) from a plasma as a function of magnetic field with the detecting frequency f as a parameter. Curves for different f 's are separated vertically for clarity. Xe, $p = 0.6$ Torr, $I_d = 150$ mA, (a) Anomalous cyclotron emission. (b) Anomalous bremsstrahlung.

FIG. 2. $f_b - f$ diagrams obtained from FIG. 2.

PHOTO. 1. Anomalous emission (upper trace) and lf oscillation picked up from anode (lower trace).

(a) Anomalous cyclotron emission ($f \approx f_b \approx 143$

Mc/s). Xe, $p = 0.34$ Torr, $I_d = 90$ mA; sweep rate, 50μ sec/div; lf oscillation, 0.1 volt/div.

(b) Anomalous bremsstrahlung ($f = 30$ Mc/s, $f_b = 0$).

Xe, $p = 0.6$ Torr, $I_d = 52$ mA; Sweep rate, 100μ sec/ div, lf oscillation, 2 volt/ div.

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Fig. 1 (a) Cyclotron frequency f_b (Mc/s)

Fig. 1 (b) Cyclotron frequency f_b (Mc/s)

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Fig. 2

PHOTO. 1. Anomalous emission (upper trace) and lf oscillation picked up from anode (lower trace).

(a) Anomalous cyclotron emission ($f \approx f_b \approx 143$ Mc/s). Xe, $p = 0.3$ Torr, $I_d = 90$ mA; sweep rate, 50μ sec/div; lf oscillation, 0.1 volt/div.

(b) Anomalous bremsstrahlung ($f = 30$ Mc/s, $f_b = 0$). Xe, $p = 0.6$ Torr, $I_d = 52$ mA; sweep rate, 100μ sec/div. lf oscillation, 2 volt/div.