REFLECTION OF ELECTROMAGNETIC WAVES FROM A PLASMA MOVING IN SLOW-WAVE GUIDES

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Electromagnetic wave reflections from a moving plasma were investigated experimentally. It was found that when the wave was greatly slowed down [(1/200) — (1/375) c] the double Doppler effect observed in reflection increased the frequency by 11 — 20%. The measurements were carried out at 24.75 Mcs. The slow-wave structure was a helix. The possibility is indicated of using this effect to amplify microwaves and to multiply their frequencies, to improve the dynamic stability of the plasma, and to perform measurements in plasma.

It is known that reflection from a moving mirror entails a change in the frequency and amplitude of an incident electromagnetic wave. Under ordinary conditions the magnitude of this effect is negligible. There are two possibilities of increasing this effect — either to increase the velocity of the reflecting surface[1] or to decrease the phase velocity of the wave in the space where the interaction takes place.[2,3] In addition, the effect can be multiplied repeatedly.

Serious difficulties arise in using the first possibility. Naturally, an ordinary macroscopic object cannot acquire a velocity close to c. To produce a reflecting surface one could use an electron beam[1] or a plasma. But to effect the reflection it is essential that the dielectric constant of the reflecting medium be either negative or of sufficiently large absolute magnitude. Since the frequency is much greater in a reference system where the reflecting medium is at rest than in the laboratory system, larger charge densities are necessary if such values of ϵ are to be obtained.* Under these conditions it is impossible to impart relativistic velocities to the plasma.

Another possibility of increasing the effect of reflection becomes available if the velocity of the electron beam of the plasma V_{pl} or even of a macroscopic object remains small, but the phase velocity V_{ph} in the interaction space is considerably reduced. In this case

$$\omega_{ref} = \omega_{inc} \frac{1 + V_{pl}/V_{ph}}{1 - V_{pl}/V_{ph}}, \qquad V_{ph} = \frac{c}{\sqrt{\varepsilon}}. \qquad (1)$$

Therefore, if the beam velocity or the plasma velocity are close to the phase velocity of the wave, the change in frequency can be quite considerable.

*Reflection takes place also at large plasma conductivities.

It can be shown that in this case the energy reflected from the moving plasma of the wave also increases considerably. The gain in this case is[2,4]

$$R = \left|\frac{1 + V_{pl}/V_{ph}}{1 - V_{pl}/V_{ph}}\right|^2 \left|\frac{1 - m}{1 + m}\right|^2, \qquad V_{ph} < c, \qquad (2)$$

where

$$m = \left[1 - \alpha_n \frac{1 - \varepsilon\beta^2}{(1 - \beta^2)\varepsilon}\right]^{1/2}, \qquad \alpha_n = \frac{p^2}{1 - (-1)^n h},$$

$$p^2 = \frac{4\pi n e^2}{m_0 \omega^2}, \qquad h = \frac{eH_0}{m_0 c\omega}.$$

Relation (2) allows us to determine the plasma density and the intensity of the magnetic field at which effective reflection is ensured at a given frequency. The increase in frequency and amplitude can be considerable if the effect considered is repeated many times.

In the present work we have investigated the effect of reflection from the plasma moving in a medium where $V_{ph} < c$. The phase velocity can be reduced by using waveguide systems of the helix type or other slow-wave structures, or else by using the waveguide properties of a low-density plasma produced in the interaction space. If an external magnetic field is applied to such a system, its phase velocity can be varied over a very wide range.

To observe the foregoing effect experimentally, we constructed the setup whose block diagram is shown in Fig. 1. The electromagnetic wave was slowed down by means of a helical waveguide, comprising a porcelain tube 40 mm in diameter on which a helix of 0.4 mm copper wire was wound at a pitch of 0.8 mm. The experimentally measured value of the first velocity of the wave in the helix was $V_{ph} = 1/_{200}$, which was somewhat less than the calculated value $V_{ph} = 1/_{150}$, obviously

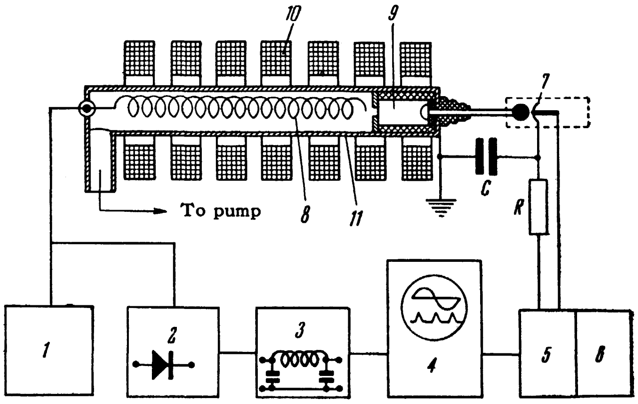

FIG. 1. Block diagram of the setup. 1 – generator, 24.75 Mcs, 2 – mixer, 3 – low-pass filter, 4 – pulse oscillograph, 5 – triggering device, 6 – rectifier, 7 – discharge gap, 8 – slow-wave system, 9 – discharge chamber, 10 – magnetic field coils.

as the result of the effect of the layer of glue between the turns. The phase velocity was measured by the standing-wave method, i.e., the wavelength λ was determined in such a waveguide by measuring the distance between neighboring minima of the standing wave with subsequent recalculation $V_{ph} = \lambda f$. The plasma piston was produced by discharging a capacitor bank of total capacitance 750 μf, charged to 4.5 kv across the discharge gap. The shape of the electrodes, their dimensions, and the distances between them were suitably chosen to produce a maximum velocity of the plasma piston.[5] To make use of the high plasmoid velocity, the plasma source and the slow-wave system were placed as close to each other as possible on a common longitudinal axis, and a longitudinal magnetic field of approximately 600 oe was applied to the entire system.

A generator operating at $f = 24.75$ Mcs was coupled weakly to the helix through a transmission line and a matching device. In order to separate the frequencies of the incident and reflected waves, a nonlinear element (a mixer connected through a low-pass filter to the pulse oscillograph) was added to the transmission line. When the wave was reflected from the leading front of the plasma piston, the incident and reflected frequencies, f_{inc} and f_{ref}, were mixed in the nonlinear element. The resultant outputs of the element were the frequencies f_{inc}, f_{ref}, $f_{inc} + f_{ref}$, and $f_{ref} - f_{inc}$, but the low-pass filter allowed only the lowest (difference) frequency to be applied to the oscillograph. All the higher frequencies were blocked by the filter, the cutoff frequency of which was 8 Mcs.

Figure 2 shows one of the oscillograms obtained. According to the sweep time scale, the difference frequency is 2.75 Mcs, corresponding to a reflected-wave frequency 11% higher than that of the incident wave. A series of experiments was then performed

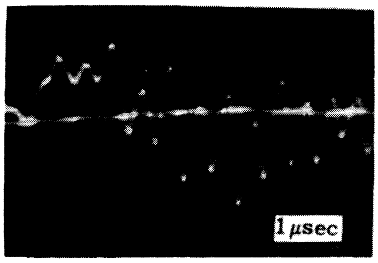

FIG. 2. Oscillogram of the difference frequency $f_{ref} - f_{inc}$.

with the helix, in which the first velocity was reduced to $1/375$ of the velocity of light. This led to a corresponding increase in the frequency of the reflected wave and the increase of this frequency amounted to 20%.

These changes in the frequency of the reflected wave correspond to a plasma-piston velocity of 8.45×10^6 cm/sec, which agrees with the work of Josephson, whose data were used to construct a plasmoid source. An independent measurement of the velocity of the front of the plasma piston with the aid of piezoelectric elements yielded $V_{pl} = 6 \times 10^6$ cm/sec.

We can therefore take it for granted that the Doppler frequency shift is greatly increased in reflections in the region where the phase velocity of electromagnetic waves is greatly reduced, $V_{ph} \ll c$.

We note that the reflection of the electromagnetic wave from the moving plasma is used by Hey, Pinson, and Smith to measure the velocity of a plasma.[6] However, since the reflection did not take place in a retarding medium, this effect was very small. The frequency shift amounted to 10^{-5}, i.e., it was 50,000 times smaller than in the case considered here: reflection from a plasma moving in a retarding medium.

This effect can be used to amplify and generate microwaves, to accelerate particles, and to perform various measurements in plasma, and also to ensure dynamic stability of a plasma.

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2