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CYCLOTRON RESONANCE ECHO*

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We have observed strong echoes radiated from a partially ionized gas plasma following excitation by a sequence of short pulses at the electron cyclotron resonance frequency. These signals have been observed only when the exciting microwave radiation is propagating perpendicular to the magnetic field, and have decay constants which we believe are determined by the electron relaxation processes in the plasma.

The simplest example of an electromagnetic echo is the two-pulse echo. A system consisting of a large number of resonators is excited by a short intense pulse of radiation, followed at a time τ by a second pulse. The second pulse triggers the coherent emission of part of the stored energy as an echo pulse which is radiated at the interval τ after the second pulse (Echo I, Fig. 1). The two-pulse-echo decay constant is observed by increasing τ and noting the rate at which the echo amplitude decreases. A three-pulse stimulated echo is obtained when a third radiation pulse is applied at some time T after the first two pulses. The stimulated echo is observed at the interval τ after the third pulse and its amplitude (Echo II, Fig. 1) is a function of both T and τ. The stimulated-echo decay constant is found by varying T alone. Echoes were first observed for nuclear paramagnetic resonance,[1] and subsequently from electron spin resonance,[2] optical transitions in atoms,[3] and ferrimagnetic resonance.[4] Our resonant system consisted of the free electrons in an afterglow plasma, immersed in a slightly inhomogeneous magnetic field. The plasma was produced by ionizing a gas, Ar, Ne, or N_2, contained in a rectangular, glass bottle with a pulsed 21-Mc/sec transmitter. The X-band microwave apparatus was similar to that used for the ferrimagnetic echo experiment.[4] The glass bottle replaced the cavity and was illuminated by microwave horns designed to produce plane waves. Typically, we set the microwave oscillator at some frequency between 8.2 and 12.4 Gc/sec and varied the magnetic field, $\vec{H}_{dc}$, for a maximum echo. The maximum echo always occurred very near the field for free electron cyclotron resonance, within the uncertainty introduced by the inhomogeneity of the magnetic field.

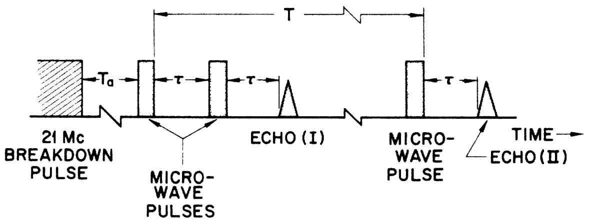

FIG. 1. Schematic representation of the time sequence of breakdown pulse, microwave pulses, and echoes for cyclotron-resonance echo experiment.

The largest echoes, with a signal-to-noise ratio of 10^5, were observed in a Ne plasma at $(5\text{-}10)\times10^{-3}$ Torr, an estimated electron density of $5\times10^9/\mathrm{cm}^3$, and a field inhomogeneity in the plasma of about 0.6%. The magnetic field inhomogeneity improves the time definition of the echo.[1] An oscilloscope picture of a representative echo signal is shown in Fig. 2. One or more secondary echoes (Fig. 2) were observed at the maximum microwave power of 15 W. The strength of the echo signal, representing at maximum 10^{-2} to 10^{-3} of the absorbed incident power, enabled us to vary most of the microwave and plasma parameters over a considerable range while still observing an echo. For this brief note we present only the effect of varying the direction of propagation and those parameters which influence the echo decay constants.

We were able to observe an echo only when

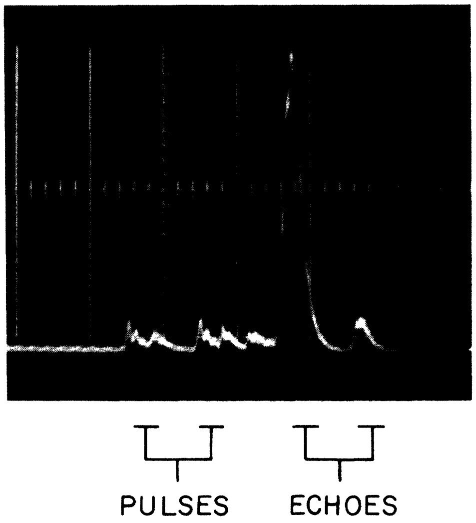

FIG. 2. Oscilloscope photograph of primary and secondary two-pulse cyclotron-resonance echoes in a Ne afterglow. The time scale is 200 nsec/cm. T_a is 0.4 msec, and the gas pressure is 5×10^{-3} Torr. The two excitation pulses appear distorted and suppressed due to receiver gating.

the direction of propagation, $\vec{k}$, and the microwave electric field $\vec{E}$ are both normal to $\vec{H}_{dc}$. Absorption near cyclotron resonance occurred when the microwave signals were incident on the plasma either normal or parallel to $\vec{H}_{dc}$, but no echo could be found for parallel propagation. This strongly suggests that the mechanism responsible for the echo is limited to the interaction of the electrons with electromagnetic fields propagating normal to $\vec{H}_{dc}$. This interaction should be nonlinear since the treatment of cyclotron resonance as a collection of harmonic oscillators whose response is linearly proportional to the incident fields cannot give rise to a radiated echo. As an electron gains energy from the incident pulses, the diameter of its cyclotron orbit increases. This introduces a phase modulation proportional to the extent of its motion along the direction of propagation, giving rise to a nonlinear interaction between the electron and the incident fields. This is a possible mechanism from which an echo will result. Work is presently in progress here to determine the magnitude of this effect.

The experimental parameters which affect the two-pulse echo and stimulated echo decay constants have led us to conclude that these decays are determined by the relaxation of the coherence and magnitude, respectively, of the electron motion induced by the exciting microwave pulses. The two decay constants differ by two orders of magnitude, reflecting the fact that in each elastic collision with a heavy atom the electron's phase and momentum are randomized but very little energy is exchanged. We observed that increasing the collision rate between electrons and neutral atoms by raising the pressure decreased the two-pulse-echo decay constant. This decay rate was also enhanced by rapid diffusion along the inhomogeneous field which occurs during and just after the 21-Mc/sec pulse. In fact, no echo at all is observed during the active discharge. Typical values of the two-pulse-echo decay constants range from 50 to 200 nsec.

The stimulated-echo decay constant depended strongly on the kind of gas used. In the rare gases Ar and Ne the stimulated echo decay constant was between 10 and 20 μsec, while in N_2 it was reduced to less than 1 μsec for the same pressure. These times are very long compared to electron–neutral-atom collision times for our experimental conditions. The marked difference between the decay in N_2 and the rare gases is apparently due to the more rapid energy relaxation provided by the closely spaced rotational and vibrational levels in N_2. Cyclotron echo could become a useful method for studying electron interactions in plasmas.

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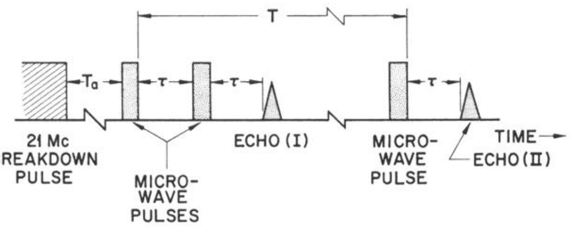

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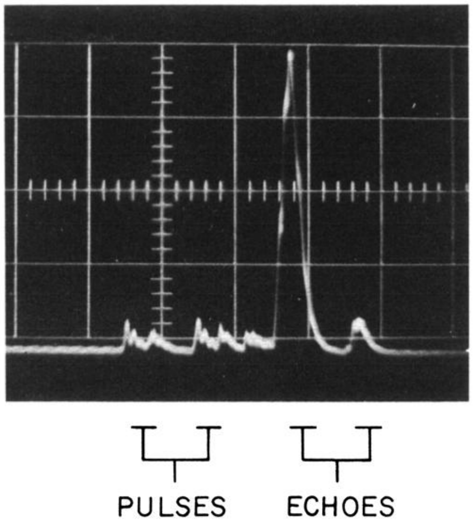

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