[1]Calculations done for the INTOR plasma parameters indicate that one need remove only (0.5–1)% of the He (Clifford Singer, private communication).
[2]U. S. Department of Energy Report No. DOE/ER-0034, 1979, edited by J. M. Rawls (unpublished).
[3]J. F. Schivell, Princeton Plasma Physics Laboratory Report No. 1342, 1977 (unpublished).
[4]A. Gondhalekar *et al.*, in *Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, 1978* (International Atomic Energy Agency, Vienna, 1979), Vol. I, p. 269.
[5]K. Uegara *et al.*, Plasma Phys. 21, 89 (1979).
[6]L. S. Scaturro and B. Kusse, Nucl. Fusion 18, 1717 (1978).
[7]W. Eckstein and H. Verbeek, J. Nucl. Mater. 76/77, 365 (1978).
[8]W. Eckstein, F. E. P. Matschke, and H. Verbeek, J. Nucl. Mater. 63, 199 (1976).
[9]E. S. Marmar, J. Nucl. Mater. 76/77, 59 (1978).

Production of Large-Amplitude Cyclotron Waves on an Intense Relativistic-Electron Beam for Collective Ion Acceleration

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(Received 20 October 1980)

Large-amplitude, low–phase-velocity, axisymmetric electron cyclotron waves have been excited and propagated more than 10 wavelengths on an intense relativistic-electron beam transported along a magnetic field inside a cylindrical vacuum waveguide. Measurements of wavelength and azimuthal symmetry have been accomplished. Wave-phase-velocity control, essential for collective ion acceleration, has been demonstrated by spatially varying the magnetic field strength. From measured wave quantities, on-axis accelerating fields of 10 MV/m are inferred.

PACS numbers: 52.60.+h, 52.35.Hr, 41.80.Dd, 29.15.-n

Among the proposed[1] methods of collective ion acceleration is the autoresonant-accelerator concept[2] which employs an axisymmetric slow cyclotron wave impressed on a very intense electron beam. In this scheme the ions are initially trapped by the wave potential in a high–magnetic-field, low–phase-velocity region and then accelerated as the phase velocity is increased by flaring the magnetic field. In this paper, the excitation, propagation, and identification of this mode on a high-power electron beam are reported. The azimuthal-mode number and wavelength of this mode have been measured. In addition, control of the wave phase velocity by spatial variation of the guide–magnetic-field strength has been demonstrated. These waves have been generated at levels of interest for collective ion acceleration.

The experimental setup is shown in Fig. 1. The 2.25-MV, 20-kA pulsed electron beam is produced in a vacuum diode employing a 5-cm-diam hemispherical cold cathode and a planar anode with a 6-cm-diam aperture through which the beam is extracted. The diode is immersed in a 2.5-kG axial magnetic field. Experimental measurements are made during an 80-ns time window when the diode voltage is constant to within 5%.

The electron beam is propagated along a guide magnetic field interior to a 7.6-cm-diam conducting drift tube which is evacuated to 10^{-6} Torr. Beam propagation has been studied with use of total collecting and multiport Faraday cups,[3] magnetic-field probes, wall charge collectors, and collimated x-ray detectors and has been found to be well behaved. In particular, the radial current-density profile has been measured to be uniform with a diameter of 5.0 cm.

The antenna used to launch the waves is located approximately 1 m from the diode, and consists of a resonant (239 MHz) half-wavelength coaxial

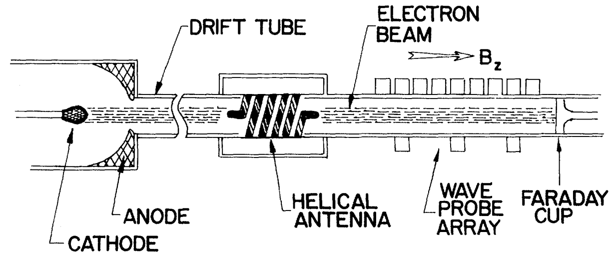

FIG. 1. Cross-sectional view of experimental arrangement.

transmission line of 17.6 cm outer diameter with a 10-cm-diam helical center conductor through which the beam propagates. The right-handed, bifilar center conductor is wound with a 5° pitch angle and is 7 cm in length. A 100-kW external oscillator, tuned to 239 MHz, inductively drives this high-Q antenna structure, in an axisymmetric mode, to the 2-MW level just prior to the beam pulse. The beam cyclotron wavelength is matched to the wavelength of the transmission line mode by adjusting the guide magnetic field to 3.5 kG. To surpress unstable high-frequency ($f \gtrsim 1$ GHz) asymmetric beam modes, which grow from beam noise, the undriven end of the antenna is loaded with a lossy dielectric material (Eccosorb HF-2050).

Wave measurements are made with a calibrated probe array located 1 m from the antenna. The probes, which are oriented to couple the axial magnetic field of the wave, are arrayed along the cylindrical coordinates z and θ to make wavelength and azimuthal-mode determinations. The technique used to perform these measurements has been described in detail elsewhere.[4] Briefly, phase comparisons are made between a reference probe signal and signals from probes at other locations with use of double-balanced mixer circuitry. In practice, either a complete wavelength or mode measurement can be made on a single machine firing.

Previously, the cyclotron mode has been excited in a low-power–model experiment[5] and on a low-current relativistic beam.[6] In our case, cyclotron waves are generated on a high-current relativistic beam by the beam-antenna interaction. A typical antenna signal, which is shown in Fig. 2, covers the time window of the voltage flat top. The antenna signal is observed to increase in amplitude with an approximately 50-ns e-folding time for the entire electron-beam pulse reaching circulating power levels in excess of 3 GW.

The wave generated by the antenna propagates to the wave-diagnostic section located about 1 m downstream. An example of a B_z probe signal is shown in Fig. 3. A Fourier transform of this signal shows it to be at the antenna driving frequency.

The azimuthal-mode number of the wave is measured by simultaneously examining the relative phase of signals from four probes equally spaced about the azimuth at a common axial location. An example of the mixer phase signals from these probes is shown in Fig. 4. These signals are seen to be in phase during the time window 160–210 ns. In fact, a least-squares best fit to the normalized phase data indicates that the wave is 90% axisymmetric ($m = 0$). Since the signal-to-noise ratio of the high-frequency signals is only about 8:1, then to the accuracy of the measurement the beam perturbation is totally axisymmetric.

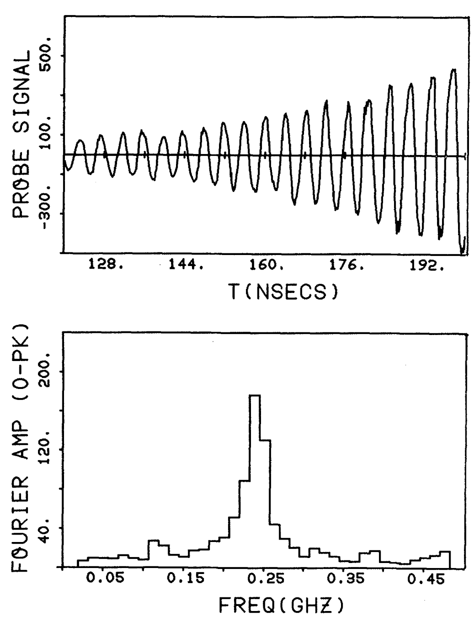

FIG. 2. Waveform of a probe signal located interior to the helical antenna, showing temporal growth due to interaction with the electron beam.

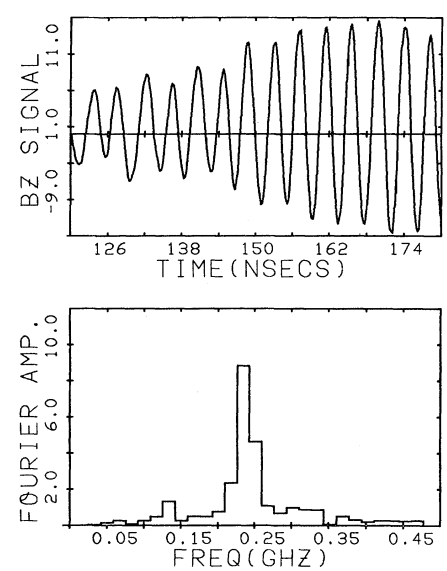

FIG. 3. Waveform from a B_z probe located in the wave probe array 1 m downstream of antenna.

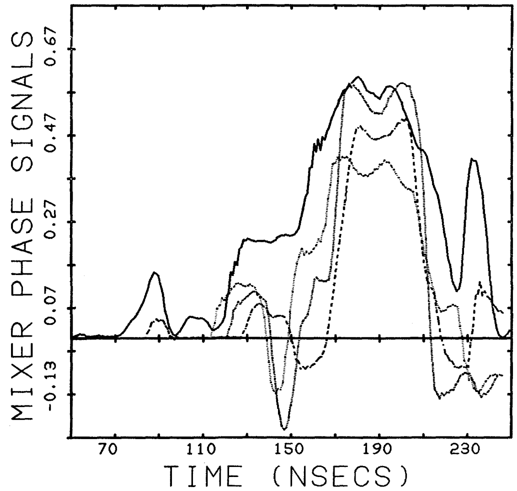

FIG. 4. Overlay of phase signals from an azimuthal array of four probes at the same axial location but 90° apart in angular position.

The theory of the axisymmetric negative-energy electron cyclotron eigenmode on a cold, relativistic-electron beam streaming along a guide magnetic field inside an evacuated conducting guide has been examined in detail.[7,8] For the parameter range of interest to these experiments, this mode has the approximate dispersion relation

$$\omega = k_z v_b - \Omega, \tag{1}$$

where ω is the driven-wave frequency; k_z is the axial component of the wave vector; v_b is the electron-beam velocity; and $\Omega = eB/\gamma mc$. Here e/m is the electron charge-to-mass ratio; γ, the electron relativistic factor; c, the speed of light; and B, the magnetic guide-field strength. From Eq. (1), by using our experimental parameters as given and including the effect of space-charge-potential depression in the computation of γ, it is calculated that a 239-MHz cyclotron wave propagating along a 3.5-kG guide field should exhibit a wavelength of 13 cm.

The wavelength of the observed wave was measured experimentally with signals from an axial array of five probes covering a 20-cm span. The amplitude and phase information were recorded simultaneously on each machine shot. The amplitude signals were spatially constant, demonstrating that a single traveling wave, rather than a standing wave, had been launched. The probe phase signals were normalized to the reference probe amplitude and plotted versus probe axial position. The wavelength as a function of time was determined by fitting a single-free-parameter least-squares best fit cosine wave to the data as shown in Fig. 5. The fit yields a wavelength of 12.5 ± 1 cm in agreement with the predicted cyclotron wavelength. Furthermore, the measured wavelength is constant throughout the voltage flat top.

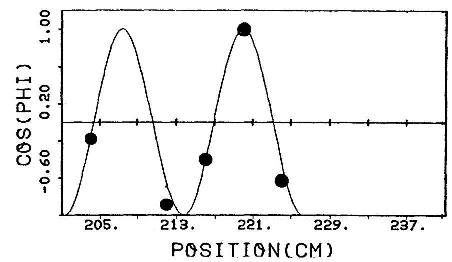

FIG. 5. Normalized phase signals (cos φ) averaged over the time window 110–190 ns vs probe distance from the anode. The circles are the experimental data and the solid line is the single-free-parameter best-fit cosine function. The reference probe is at 220 cm.

In order to accelerate ions in the collective electric fields of this cyclotron wave it is necessary to increase spatially the wave phase velocity. This may be accomplished by an adiabatic spatial decrease in the guide-magnetic-field strength, as may be seen from Eq. (1):

$$v_{\rm ph}(z) \equiv \omega/k_z = v_b\,\omega/[\omega + \Omega(z)], \tag{2}$$

where ω is a constant (239 MHz) wave frequency.

This phase-velocity-control feature of the elec-

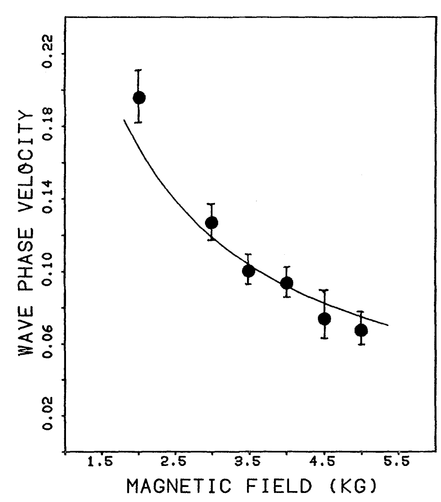

FIG. 6. Measured wave phase velocity vs guide-magnetic-field strength. The solid curve is the theoretical prediction.

tron cyclotron mode has been demonstrated experimentally by maintaining a fixed magnetic-field strength at the antenna and then adiabatically varying the downstream field strength while monitoring the wavelength in this region. In Fig. 6 the measured wave phase velocity is plotted versus guide-field strength. The solid curve is the theoretical prediction [Eq. (2)], which is in excellent agreement with the data.

Finally, it is possible to determine the cyclotron-wave-accelerating electric-field amplitude on axis from the measured wave magnetic-field perturbation level at the drift-tube wall with use of an accurate theoretical description of the cyclotron eigenmode. The most complete theoretical model available includes equilibrium radial γ variation and nonlinear corrections associated with resonance broadening due to wave-related finite perpendicular velocities.[9] From measured wave magnetic-field perturbations, which are in excess of 50 G, wave potentials in excess of 120 KV (zero to peak) are inferred, with on-axis accelerating fields of 10 MV/m.

The authors would like to thank W. E. Drummond, coinventor of the autoresonant-acceleration process, for his encouragement and helpful discussions; also J. Jagger and P. Snowden, for their invaluable technical advice. In addition, we would like to express our appreciation to H. V. Wong, J. R. Thompson, B. N. Moore, and G. I. Bourianoff for their valuable theoretical assistance.

This work was supported by the U. S. Army Ballistic Missile Defense Advanced Technology Center under Contract No. DASG60-76-C-0045.

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[1]*Collective Methods of Acceleration*, edited by N. Rostoker and R. Reiser (Harwood, New York, 1978).

[2]W. E. Drummond and M. L. Sloan, Phys. Rev. Lett. 31, 1234 (1973).

[3]T. P. Starke, Rev. Sci. Instrum. 51, 1700 (1980).

[4]H. A. Davis and Edward Cornet, Rev. Sci. Instrum. 51, 1176 (1980).

[5]B. I. Ivanov *et al.*, in Proceedings of the Third International Conference on High Power Electron and Ion Beams, Novosibirsk, USSR, 1979 (to be published).

[6]G. Providakes and J. A. Nation, J. Appl. Phys. 50, 3026 (1979).

[7]W. E. Drummond *et al.*, Air Force Weapons Laboratory Report No. AFWL-TR-75-296, 1975 (unpublished).

[8]Brendan B. Godfrey, IEEE Trans. Plasma Sci. 7, 53 (1979).

[9]H. V. Wong, Austin Research Associates, Austin, Texas, Report No. I-ARA-79-U-72, 1979 (unpublished).

Vortex Solitons of Drift Waves and Anomalous Diffusion

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It is shown that two-dimensional solitons, being vortices propagating at characteristic speeds, can be formed in a long-wavelength drift-wave turbulence. A random set of vortex solitons scatters plasma particles and leads to enhanced diffusion, whose coefficient can become as large as that due to convective cells.

PACS numbers: 52.35.Mw, 52.25.Fi, 52.35.Kt

Nonlinear drift waves have been studied in connection with enhanced diffusion in magnetic confinement devices.[1-4] The recent theory of drift-wave turbulence showed that the energy of drift wave is likely to condense at a long-wavelength region due to nonlinear wave-wave interaction[2]: $k_y \approx 0$ and $k_x\rho_s \sim (\kappa\rho_s)^{1/3} \equiv k_c\rho_s$, where k_y is the wave number in the direction of the diamagnetic drift, x is the direction of density inhomogeneity, κ $(= -d\ln n_0/dx)$ is the measure of inhomogeneity, ρ_s $[=(T_e/M)^{1/2}/\omega_{ci}]$ is the effective ion Larmor radius, T_e is the electron temperature, M is the ion mass, and ω_{ci} is the ion cyclotron frequency.

It was found that, consistent with this theory, two-dimensional drift-wave solitons can exist with $k_x\rho_s$ of order unity and $k_y\rho_s \ll 1$.[3] However, when k_y becomes so small that $k_z/k_y \sim \kappa\rho_s$ (k_z is the wave number in the direction of the ambient magnetic field $B_0\hat{z}$), we must take into account the finite-k_z effect, which was neglected in Refs. 1–3. The effect of finite k_z brings about the steepening nonlinearity, which is the same as that

