174
1/17/85
PPPL-2178

UC20-F

1-18956

PPPL-2178

DR-0731-5

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE

It has been reproduced from the best available copy to permit the broadest possible availability.

OBSERVATION OF THE BACKWARD ELECTROSTATIC ION CYCLOTRON WAVE

By

J. Goree, M. Ono, and K.L. Wong

DECEMBER 1984

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CO-3073.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America

Available from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price Printed Copy \$ ____ * ; Microfiche \$4.50

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-25	\$7.00
25-50	\$8.50
51-75	\$10.00
76-100	\$11.50
101-125	\$13.00
126-150	\$14.50
151-175	\$16.00
176-200	\$17.50
201-225	\$19.00
226-250	\$20.50
251-275	\$22.00
276-300	\$23.50
301-325	\$25.00
326-350	\$26.50
351-375	\$28.00
376-400	\$29.50
401-425	\$31.00
426-450	\$32.50
451-475	\$34.00
476-500	\$35.50
500-525	\$37.00
526-550	\$38.50
551-575	\$40.00
567-600	\$41.50

For documents over 600 pages, add \$1.50 for each additional 25-page increment.

OBSERVATION OF THE BACKWARD ELECTROSTATIC ION CYCLOTRON WAVE

J. Goree, M. Ono, and K. L. Wong

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

ABSTRACT

PPPL--2178

DE85 005340

The backward branch of the electrostatic ion cyclotron wave has been observed, we believe, for the first time. The wave, which was driven by a phased antenna structure inserted in a neon plasma, exists in the parameter ranges $2T_i/m_i \ll (\omega/k_{\parallel})^2 \ll 2T_e/m_e$, $n\Omega_i < \omega < (n+1)\Omega_i$, $T_e \gtrsim T_i$, and $\omega_{pi} > \Omega_i$. Double-tip probe interferometry data agree with the theoretical dispersion relation.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

26

The electrostatic ion cyclotron wave is the hot magnetized plasma mode with its frequency near an ion gyrofrequency harmonic and a phase velocity parallel to the magnetic field $\omega/k_{\parallel}$ less than the electron thermal velocity, but greater than the ion thermal velocity. It has also been called the neutralized ion Bernstein wave.¹

The wave was discovered by D'Angelo and Motley (1962),² who observed the acousticlike forward wave at the fundamental frequency in a cold alkali plasma. Drummond and Rosenbluth³ attributed their observation to a kinetic instability associated with parallel electron drift. Lominadze and Stepanov (1965)⁴ introduced finite Larmor radius (FLR) effects into theory, revealing for the first time this mode's backward branch.

These are the criteria which specify the electrostatic ion cyclotron wave:

$$\sqrt{\frac{2T_i}{m_i}} \ll \frac{\omega}{k_{\parallel}} \ll \sqrt{\frac{2T_e}{m_e}}, \quad (1)$$

$$n\Omega_i < \omega < (n+1)\Omega_i, \quad n \geq 1, \quad (2)$$

and $\omega_{pi} > \Omega_i$ and $T_e \gg T_i$.

The real solutions of the dispersion relation of the electrostatic ion cyclotron wave generally show two possible values for $k_{\perp}$ for a given frequency. Except for ω very near $n\Omega_i$, the shorter wavelength solution is a backward wave, i.e., the wave number vector component $k_{\perp}$ has the direction

opposite that of the group velocity. Several experiments have been reported on the forward branch,⁵⁻⁷ and Schmitt was able to observe effects of ion cyclotron harmonics through antenna loading measurements.⁸ However, observation of the backward branch was not reported in these experiments. This mode should be distinguished from the pure ion Bernstein wave, which is also backward, but is characterized by $\omega/k_{\parallel} \gg \sqrt{2T_e/m_e}$, and has no forward branch.^{1,9}

For electrostatic waves, the collisionless dispersion relation can be expressed¹⁰ as $D(\omega, k_{\parallel})=0$, where

$$D = k_{\perp}^2 K_{xx} + 2k_{\parallel} k_{\perp} K_{xz} + k_{\parallel}^2 K_{zz} \quad (3)$$

and the dielectric tensor elements K_{xx} and K_{zz} are

$$K_{xx} = 1 + \frac{\omega_{pe}^2}{\Omega_e^2} + \sum_j \frac{\omega_{pj}^2}{k_{\parallel} \omega} \frac{e^{-\lambda_j}}{\lambda_j} \sqrt{\frac{m_i}{2T_j}} \sum_{n=-\infty}^{+\infty} n^2 I_n(\lambda_j) Z(\zeta_n^j)$$

$$K_{zz} = 1 + \frac{2\omega_{pe}^2}{k_{\parallel}^2} \frac{m_e}{2T_e} \left[1 + \frac{\omega}{k_{\parallel}} \frac{m_e}{2T_e} Z(\zeta_0^e) \right].$$

and

$$K_{xz} = -\frac{k_{\perp}}{k_{\parallel}} \sum_j \frac{\omega_{pj}^2}{\omega \Omega_j} \frac{e^{-\lambda_j}}{\lambda_j} \sum_{n=-\infty}^{+\infty} n I_n(\lambda_j) [1 + \zeta_n^j Z(\zeta_n^j)].$$

Here, $\lambda_j = k_{\perp}^2 T_j / m_j \Omega_j^2$, j designates the ion species, I_n is the modified Bessel function, $\zeta_n^k = (\omega - n\Omega_k)(m_k/2T_k)^{1/2}$, and Z is the plasma dispersion function. It was assumed that $\omega \ll \Omega_e$, $\lambda_e \ll 1$, and that the distribution functions are isotropic, nondrifting Maxwellians.

By specifying the parameters of inequalities (1) and (2), this dispersion relation yields the electrostatic ion cyclotron wave solutions. Except for the acoustic wave limit,¹¹ $\lambda_j \ll 1$, the roots of the dispersion relation are most easily computed numerically. For a single ion species, the wave is forward for small values of λ_j and backward for $\lambda_j \gtrsim 1$. For all values of λ_j , the electrostatic ion cyclotron wave is prone to severe ion and especially electron Landau damping. The first term of Eq. (3) depends mostly on ion kinetics and one finds in it the FLR effects which are responsible for the backward wave. The second term is negligible and the third term, due to electrons, dominates for the forward wave.

The experiment ran on the ACT-I toroidal device¹² with a vertically uniform magnetized plasma with warm ions. A singly ionized heavy ion species, Ne^+ , was used to satisfy relations (1) and (2). Observation of the backward branch may have been unreported previously because it is difficult to satisfy these relations, to obtain warm ions, and to overcome Landau damping. An antenna structure, constructed of two blades of molybdenum plate attached to 1-mm tungsten rod, was inserted into the plasma. The blades were parallel to the magnetic field, in a vertical plane, as shown in Fig. 1.

An rf signal of several volts was applied to the antenna, the two blades phased at 180° to create a $k_{\parallel}$ spectrum peaked at 1.0 cm^{-1} . The wave launched in the plasma was detected by an rf double-tip Langmuir probe which was scanned radially to measure $k_{\perp}$ by interferometry. The probe could pass

through the gap between antenna blades, where a strong nonpropagating disturbance was found in a 1-cm thick layer. Outside this layer, the electrostatic ion cyclotron wave was observed.

The antenna blades lay perpendicular to the toroidal magnetic field gradient. The direction of this gradient affected the antenna coupling to the wave and the backward wave was usually found on the low field side of the antenna. Using probe interferometry made with an rf phase sensitive detector, we compared two radial interferometry traces, with the signal delayed by 0° and 90° , to determine the direction of $\vec{k}_\perp$. $\vec{k}_\perp$ points in the direction in which the peaks and valleys of the 0° trace appear to be shifted from those of the 90° trace. The group velocity direction is always outward from the antenna and the backward wave is identified when $\vec{k}_\perp$ is directed in toward the antenna. Such behavior is observed in the interferometry traces shown in Fig. 2. The backward wave propagates on the low field side of the antenna, and the forward wave on the high field side.

By taking data for many frequencies, we obtained the experimental dispersion relation shown in Fig. 3. A theoretical solution, Eq. (3), is also shown and the experimental data fit it well.

We thank T. H. Stix for making helpful suggestions regarding the manuscript and W. Kineyko and J. Taylor for able technical assistance. This work is supported by the U.S. Department of Energy Contract No. DE-AC02-76-CH0-3073.

References

- ¹J. P. M. Schmitt, Phys. Rev. Lett. 31, 982 (1973).
- ²N. D'Angelo and R. W. Motley, Phys. Fluids 5, 633 (1962).
- ³W. F. Drummond and M. N. Rosenbluth, Phys. Fluids 5, 1507 (1962).
- ⁴D. G. Lominadze and K. N. Stepanov, Sov. Phys. -Tech. Phys. 9, 1408 (1965).
- ⁵A. Hirose, I. Alexeff, and W. D. Jones, Phys. Fluids 13, 2039 (1970).
- ⁶E. R. Ault and H. Ikezi, Phys. Fluids 13, 2874 (1970).
- ⁷T. Ohnuma et al. Phys Rev. Lett. 26, 541 (1971).
- ⁸J. P. M. Schmitt, Phys. Fluids 15, 2057 (1972).
- ⁹M. Ono and K. L. Wong, Phys. Rev. Lett. 45, 1105 (1980).
- ¹⁰T. H. Stix, Theory of Plasma Waves, Ch.9, (McGraw-Hill, N.Y., 1962).
- ¹¹Ref. 10, Ch. 2.
- ¹²K. L. Wong, M. Ono, and G. Wurden, Rev. Sci. Instrum. 53, 409 (1982).

Figure Captions

- Fig. 1. The geometry of the antenna, drawn to scale, as viewed from the side of the torus. Plasma is shown shaded.
- FIG. 2 Probe interferometry traces of the electrostatic ion cyclotron wave in a neon plasma. The wave was launched with frequency $\omega/2\pi = 440$ KHz ($\omega/\Omega_i = 1.33$) on the fundamental mode branch. The traces were made while delaying the probe signal by either 0° or 90° compared to the oscillator driving the antenna. The direction of $\vec{k}$ points from valleys in the 90° trace to valleys in the 0° trace, and from hills in the 90° trace to hills in the 0° trace. The forward wave, by definition, has $\vec{k}_\perp$ in the same direction as the group velocity, which is always away from the antenna. The backward wave is seen at the left, on the low field side of the antenna. The strong nonpropagating disturbance between the antenna blades is not shown, for clarity.
- Fig. 3. The dispersion relation of the electrostatic ion cyclotron wave in the same neon discharge used in Fig. 2. The solid curve is a numerical solution assuming $k_\parallel = 1.0 \text{ cm}^{-1}$, $T_e = 2.1 \text{ eV}$, $T_i = 0.4 \text{ eV}$.

#84X0785

Fig. 1

Fig. 2

#84X1784

Fig. 2

EXTERNAL DISTRIBUTION IN ADDITION TO TIC UC-20

Plasma Res Lab, Austre Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. D. Pelumbo, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakaneke, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
 Zhengwu Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, Academia Sinica, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-CE6, FRANCE
 AM Dupas Library, AM Dupas Library, FRANCE
 Dr. Tom Mual, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. S.K. Trehan, Punjab University, INDIA
 Dr. Indra, Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chevda, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Var Ruchi Marg, INDIA
 P. Kow, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ DI Padova, ITALY
 Librarian, Inst Theo Phys, ITALY
 Miss Clelia De Palo, Assoc EURATOM-CNEN, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. M. Yoshikawa, JAERI, Tokai Res Est, JAPAN
 Prof. T. Uchida, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigeru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Tech Info Division, Korea Atomic Energy, KOREA
 Dr. R. England, Ciudad Universitaria, MEXICO
 Bibliotheek, For-inst Voor Plasma, NETHERLANDS
 Prof. B.S. Liley, University of Waikato, NEW ZEALAND
 Dr. Suresh C. Sharma, Univ of Calabar, NIGERIA
 Prof. J.A.C. Cebrai, Inst Superior Tech, PORTUGAL
 Dr. Octavian Petrus, ALI CUZA University, ROMANIA
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Atomic Energy Bd, SO AFRICA
 Fusion Div, Library, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Dr. Erik T. Karlson, Uppsala Universitet, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. W.L. Weise, Nat'l Bur Stand, USA
 Dr. W.M. Stacey, Georg Inst Tech, USA
 Dr. S.T. Wu, Univ Alabama, USA
 Prof. Norman L. Olsson, Univ S Florida, USA
 Dr. Benjamin Ma, Iowa State Univ, USA
 Prof. Wagne Kristiansen, Texas Tech Univ, USA
 Dr. Raymond Askew, Auburn Univ, USA
 Dr. V.T. Tolok, Kherkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Institute Gen. Physics, USSR
 Prof. T.J. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universität, W. GERMANY
 Nuclear Res Estab, Jülich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Dr. M.J. Kaeppeler, University Stuttgart, W. GERMANY
 Bibliothek, Inst Plasmeforschung, W. GERMANY