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We observed waves of ion cyclotron range of frequencies during neutral beam injection into JFT-2 and JFT-2M tokamaks. Characteristic features of one of waves on which we put an emphasis in this report are as follows; 1) The wave appears when hydrogen beam is injected into deuterium plasma but hardly appears when the target plasma is hydrogen; 2) The appearance of the wave is concentrated in the initial phase of the beam injection; 3) Its frequency is close to the ion cyclotron frequencies at the center of the plasma; 4) The plasma density influences not on the frequency but on the duration of the oscillation; 5) The wave length was measured to be several tens centi-meter with $\lambda_{\parallel} > \lambda_{\perp}$. The resulting phase velocity ω/κ and other related velocities are put in order as $|\omega/\kappa| \gtrsim V_A \gtrsim V_b$ where V_A and V_b are the Alfven and beam particle velocities, respectively.

Another mode observed, while detailed observation has not yet been made, showed rather gradual and continuous behavior at intermediate frequencies between the ion cyclotron harmonics.

Keywords; Beam-Plasma Interaction, Neutral Beam Injection, Tokamak,
Ion Cyclotron Wave, Velocity-space Instability,
Electrostatic Probe

トカマクでの中性粒子入射時におけるイオンサイクロトロン波の観察

日本原子力研究所東海研究所核融合研究部
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（１９８４年７月３１日受理）

ＪＦＴ－２およびＪＦＴ－２ＭでのＮＢＩ実験時において，イオンサイクロトロン周波数領域の波の発生を観測した。特にある波に注目し，それが以下の性質を持つことを明らかにした。①この波の発生は H^0 ビームを D^+ プラズマに入射した時に見られるが H^+ プラズマへの入射では見られない。②波の発生は，ＮＢ入射の初期にのみ起る。③周波数としてはプラズマ中心での ω_{ci} の値をとる。④プラズマの密度は波の継続時間には影響を与えるが周波数には与えない。⑤波長は数１０㎝のオーダーである。これによる波の速度と他の関連する速度とは，$\left|\omega/k\right| \gtrsim V_A \gtrsim V_b$ の関係になる。ここで V_A は，アルフベン速度，V_b は，ビーム粒子の速度である。この波のほかに，ゆるやかでかつ連続的な時間変化を示す他種の波の存在も観察した。この波の周波数は，上記のサイクロトロン周波数およびその高調波からはなれた中間の値をとる。

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Recent promotion of tokamak plasma parameters is due mainly to the use of powerful neutral beam injection (NBI). The method is also expected to be used to ignite tokamak reactors. The introduction of energetic ion beams into plasma, however, creates a hump in the velocity distribusion of ions, which may cause instabilities and bring waves in the plasma especially in the ion cyclotron range of frequencies (ICRF). Such instabilities and waves have attracted considerable interest of scientists in connection with both basic plasma physics in tokamaks and its influence on plasma containment. In particular, Stix$^{1)}$ and lately others$^{2)}$ argued the time variation of the velocity distribution of ions and have predicted that a wave should be excited in the initial phase of NBI. Non of experimental evidence of such oscillations in tokamak experiments, however, has heretofore been presented in the literature. The TFR experiments$^{3)}$ have reported an ICRF oscillation during NBI, which seems to be somewhat defferent from that mentioned above. In this paper, we present waves in ICRF which have been observed in NBI experiments of JAERI tokamaks JFT-2 and JFT-2M. Within our present knowledge, this is the first experimental report on such a wave that agrees with the Stix's prediction concerning its time behavior. In the following, we mention experimental methods / conditions, then we present the results from the observation which consist of frequency spectrum, time behavior and wave vectors.

2. Experimental

The fundamental experimental conditions are summarized in the following table where JFT-2M$^{4)}$ has been constructed after the shutdown of JFT-2$^{5)}$.

	JFT-2	JFT-2M
Cross section	Circular	b/a = 1.1
Major radius (cm)	90	130
Minor radius (cm)	25	35
Toroidal magnetic field (T)	1.3	1.2 - 1.4
Plasma current (kA)	145	150
Average electron density (10^{13}cm^{-3})	4-5	2-3

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The plasma parameters in the table show their values before injection.

The same neutral beam injectors were applied to both tokamaks. The direction of injection was nearly tangential and the net injected power was 1 MW with co-injection. In this experiment, hydrogen beam was injected into the deuterium plasma with the energy of 30 keV.

The detection of the oscillations was made by Langmuir probes located 1-2 cm outside the limiter radius about median plane. The size of the probe head was 2 mm in length and 1 mm in diameter. The sleeve of the probe (outer conductor) was grounded so as to be in wall potential. The rear end of the probe was connected directly to the spectrum analyzer througth coaxial cable with 50 ohm terminators. Therefore, the probe signal does not represent well-defined potential (i.e. floating or space potential) but does some portion of potential fluctuation near the probe. The spectrum analyzer we used was ordinary one which sweeps frequency with time-varying heterodyne detection. This analyzer can also record time variation of an oscillation at a fixed frequency.

3. Oscillations in the initial phase of NBI

Figure 1 shows an example of a frequency spectrum of the probe signal in the ICRF when the NB was injected into the JFT-2 plasma. An apparent peak is found at 20 MHz which is just the ion cyclotron frequency of protons at the center of the plasma. It should be noted that the ion cyclotron frequency at this probe position was 15.4 MHz. When the timing of the frequency scan of the analyzer was slightly shifted, we also found an another peak at 40 MHz. Figure 2 shows time variation of these oscillations. The 20 MHz oscillation starts shortly after the NB injection and lasts about 2 ms. The 40 MHz oscillation, however, starts about the end of 20 MHz oscillation as if the most unstable frequency transferred to the 2nd harmonic owing to some changes in plasma conditions.

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It is found that the frequency closely follows the change in B_t at the cyclotron frequency of the center of the plasma.

The dependence of the frequency on the plasma density is negligibly small because the frequency characteristics did not differ between the JFT-2 (Fig. 1) and JFT-2M (Fig. 3) experiments where the average density of JFT-2 was twice that of JFT-2M. Figure 4 shows the time behavior of the fundamental oscillation (19 MHz) in the JFT-2M plasma. The upper and the lower trace were obtained when $\bar{n}_e = 3 \times 10^{13}$ cm^{-3} and $\bar{n}_e = 2 \times 10^{13}$ cm^{-3}, respectively. Taking also Fig. 2 (JFT-2) into account, we understand that the plasma density influences the duration of the oscillation: 'lower plasma density refers to longer duration of the oscillation.

Other note-worthy aspects of this mode we observed are as follows.

1) The oscillation appears when hydrogen beam is injected into deuterium plasma but hardly appears when the target plasma is hydrogen. It seems there exists some threshold of the hydrogen content for the oscillation.

2) The appearance of the harmonics in such order as Fig. 2 is generally found. However, in some particular experiments in JFT-2M we found that both the fundamental and the harmonics appeared simultaneously.

In the rest of this paper, for the convenience, we should like to designate the oscillation the transient mode, because the dominant character may be represented by its transient behavior.

4. Measurement of wave vectors of the transient mode

In order to obtain a propagation characteristics of the transient mode, we introduced a probe assembly which consists of a movable and two fixed probes and is mounted on a 100 CF frange. The movable probe scans the yz plane circumferentially with the radius of 35 mm where y and z are introduced as a local co-ordinate which correspond to the poloidal and toroidal directions, respectively. Each fixed probe was set 10 mm appart from the topmost and the leftmost circumference. Hence, the abailable minimum and maximum probe separation are 10 mm and 80 mm, respectivelly, in both perpendicular (y) and parallel (z) directions to the magnetic field. Here, for the simplicity, we

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The phase difference Θ between wave signals of one of the fixed probe and the movable one at a prescribed position were measured directly on the oscilloscope traces. Figure 5 shows an example of the oscillogram of the fundamental frequency. One measurement of Θ at a probe position (y,z) presents us a relation with unknown wave number k_y, k_z as $k_y y + k_z z = \Theta$, where the origin of (y,z) was set on the fixed probe. The measurement of Θ at different two or more probe positions, therefore, makes us possible to evaluate k_y and k_z. Figure 6 shows so obtained points of $\vec{k} = (k_y, k_z)$ which were calculated from 12 different measuring positions and total 30 plasma shots. The large scatter in the figure is attributed to the poor reproducibility in the measurement of Θ; that is, Θ fluctuated shot by shot despite the same probe position. Since this method essentially necessitate good reproducibility, most of $\vec{k}$-points in the figure have no meaning under the circumstances. However, the distribution of the points, in a global sense, may indicate the probability of the appearance of the corresponding wave number. Figure 7 shows the distribution of $\vec{k}$-points as a function of k_y and k_z obtained from Fig. 6. Note that this figure does not show the ordinary k-spectrum of a wave. It is shown that the perpendicular wave numbers concentrate about $k_y = -20\ \mathrm{m}^{-1}$ which corresponds to the wave lengeh about 0.3 m. As to parallel wave numbers the dominant peak lies around $k_z = 0$. In addition to this, we set an auxiliary probe 0.33 m apart from one of the fixed probe for the estimation of k_z. The data from the auxiliary probe represented $k_z = -6.5\ \mathrm{m}^{-1}$. Considering the accuracy of the measurement, we had better to ignore several small praks in the k_z distribution. So, we concluded that the most probable wave of the fundamental transient mode should have wave numbers as $k_y \simeq -20\ \mathrm{m}^{-1}$ and $k_z \lesssim -7\ \mathrm{m}^{-1}$. The order of the characteristic velocities may be, then, $|\omega/k| \gtrsim V_A \gtrsim V_b$ where ω/k, V_A and V_b are the phase velocity of the wave, the Alfven velocity and beam particle velocity, respectively. Concerning the direction of the propagation note should be added: positive k_y and positive k_z correspond to the direction of the ion diamagnetic current and to the direction of the injected beam.

5. Another mode in an equilibrium state

Figure 8 shows also the spectrum obtained by the JFT-2M experiment. The peaks at 19 MHz and 38 MHz have already been discussed in previous sections. The figure shows an another peak at 32 MHz. The time variation of the intensity of this oscillation is shown in Fig. 9. A remarkable difference of the time behavior from the transient mode can be found. In this figure the oscillation started 8 ms after the start of NBI and grew gradually up to a saturation level. The saturation level lasted during NBI as if the phenomena were in an equilibrium state. After the switch off of NBI the oscillation decayed also gradually. This is a contrast to that of the transient mode where the oscillation stops instantaneously at the switch off. Here, we present only the existence of this mode. Further studies are left in future. In contrast with the transient mode let us call this mode, in this paper, the equilibrium mode.

6. Discussions

In this paper, we should like to limit ourselves to presenting the experimental results. A theoretical understanding of the transient mode will be presented elsewhere6), where they study an influence of the wave excitation on the energy transfer during NBI.

The existence of ICRF oscillation during NBI on a tokamak has already been reported by the TFR experiment3). Although detailed description has not been presented, their oscillation may correspond to our equilibrium mode because the oscillogram signals showed a rather continuous mode. The transient mode, however, seems to have been first observed in our experiments.

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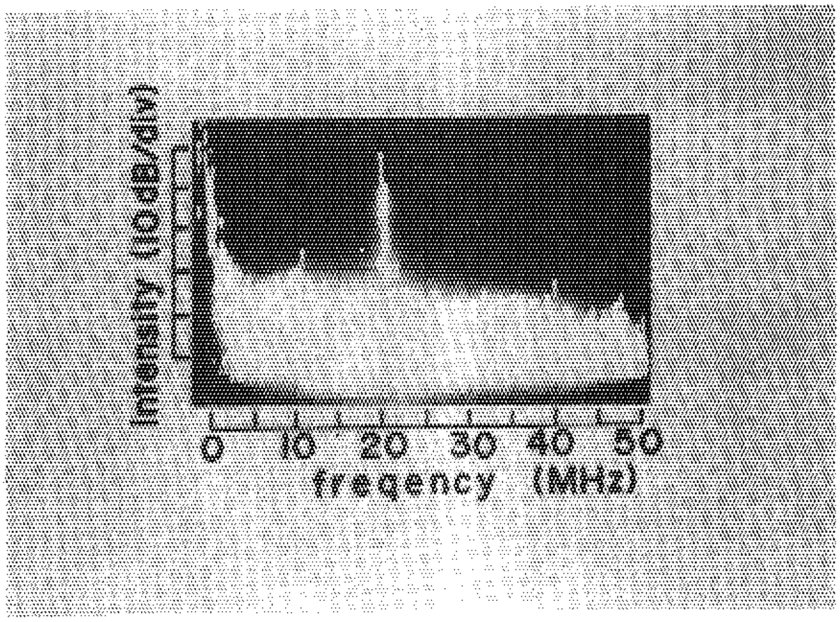

Fig. 1 Frequency spectrum obtained in early phase of NB injection into JFT-2 when B_t=1.3 T.

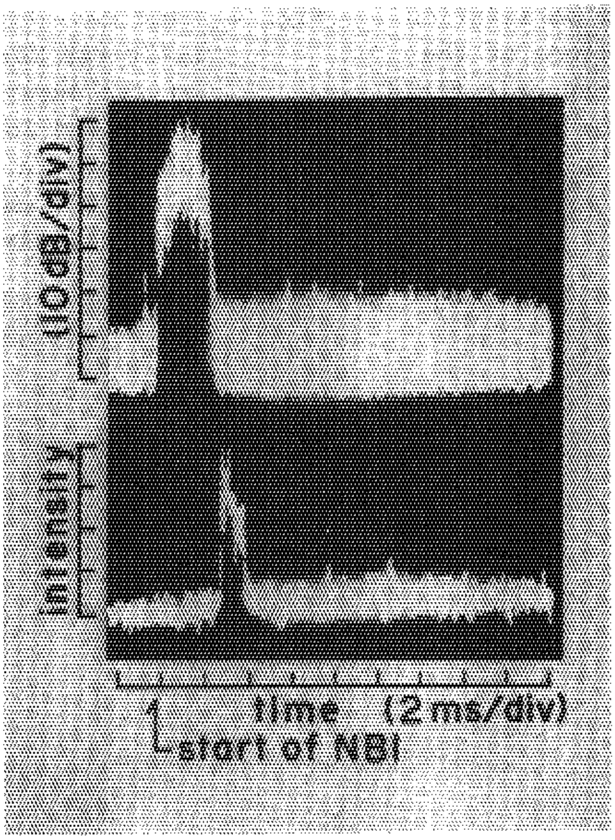

Fig. 2 Time variation of intensity of 20 MHz (upper) and 40 MHz (lower) oscillations in early phase of NB injection into JFT-2 (B_t=1.3).

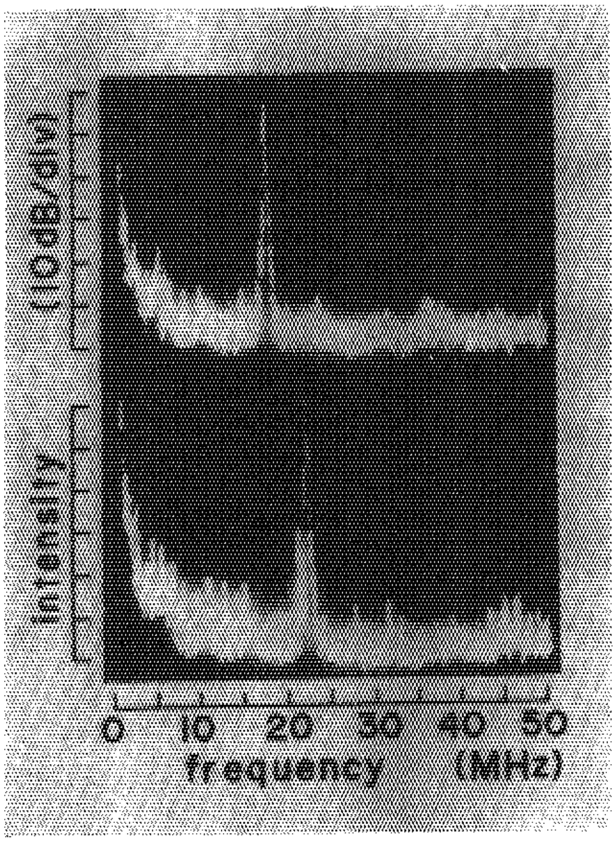

Fig. 3 Spectra of the oscillation showing dependence of the frequency on magnetic field. Upper and lower traces were obtained when B_t=1.17 T and B_t=1.42 T, respectively.

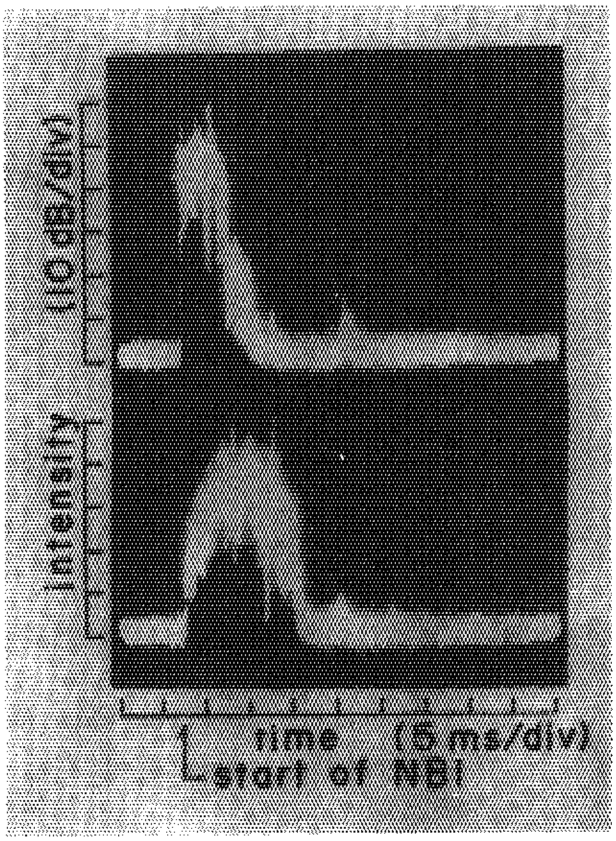

Fig. 4 Time variation of the oscillation ($\omega/2\pi$ =19 MHz) showing dependence of its duration on plasma density. Upper and lower traces were obtained in JFT-2M experiment when $\bar{n}_e=3\times10^{13}$ cm^{-3} and $\bar{n}_e=2\times10^{13}$ cm^{-3}, respectively.

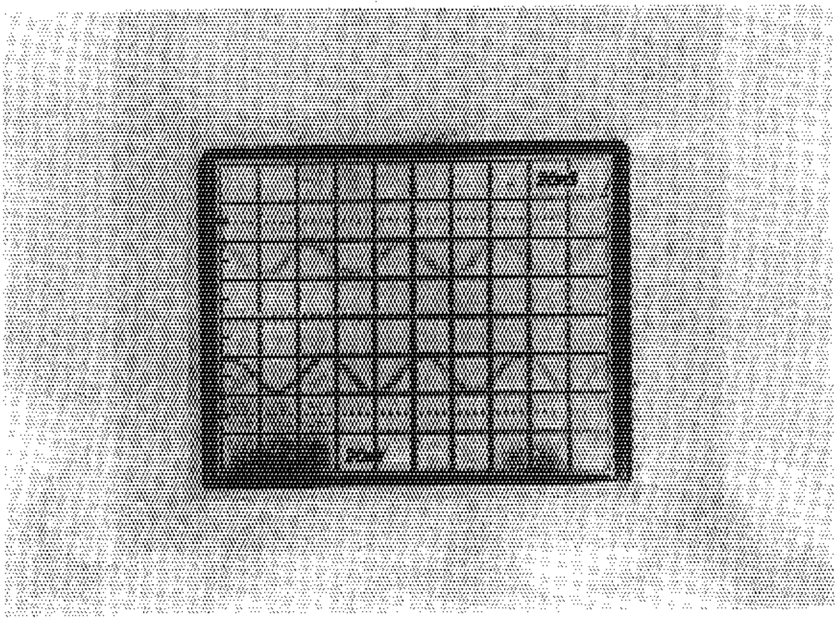

Fig. 5 Example of oscillogram trace of the phase difference between two probes when $\omega/2\pi$ =19 MHz. (20 ns/div.)

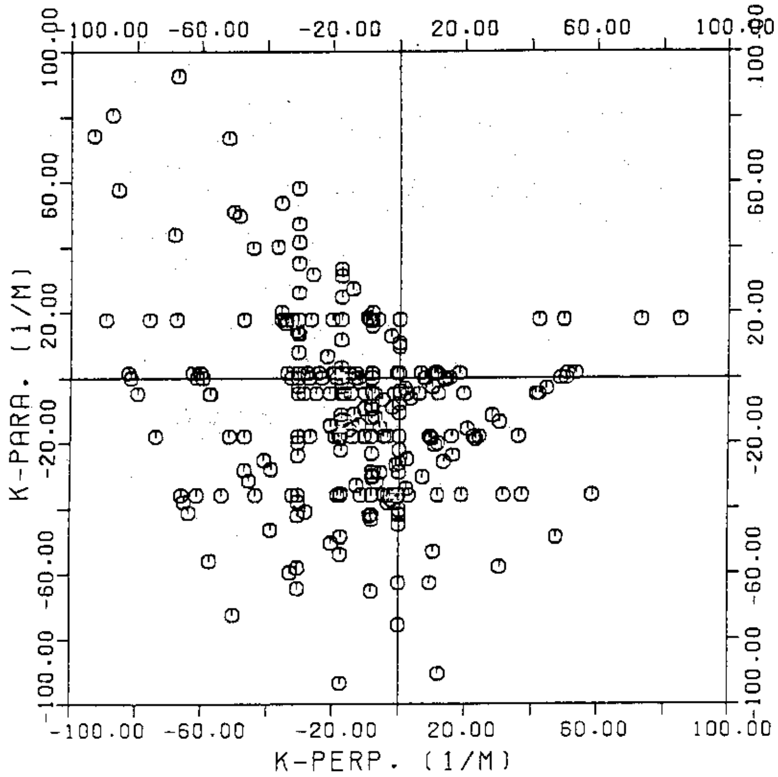

Fig. 6 Distribution of wave vectors of the transient mode ($\omega/2\pi$ =19 MHz) calculated from the probe measurement. Positive k-perpendicular (k_y) and k-parallel (k_z) correspond to directions of ion diamagnetic current and injected beam, respectively.

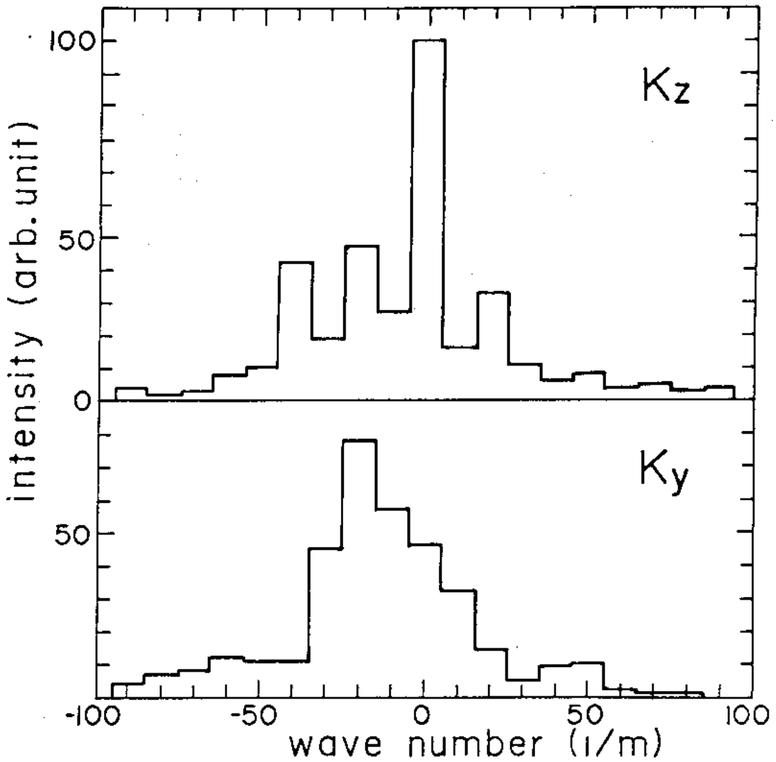

Fig. 7 Distribution of $\vec{k}$-points reduced from Fig.6 as functions of k_y and k_z.

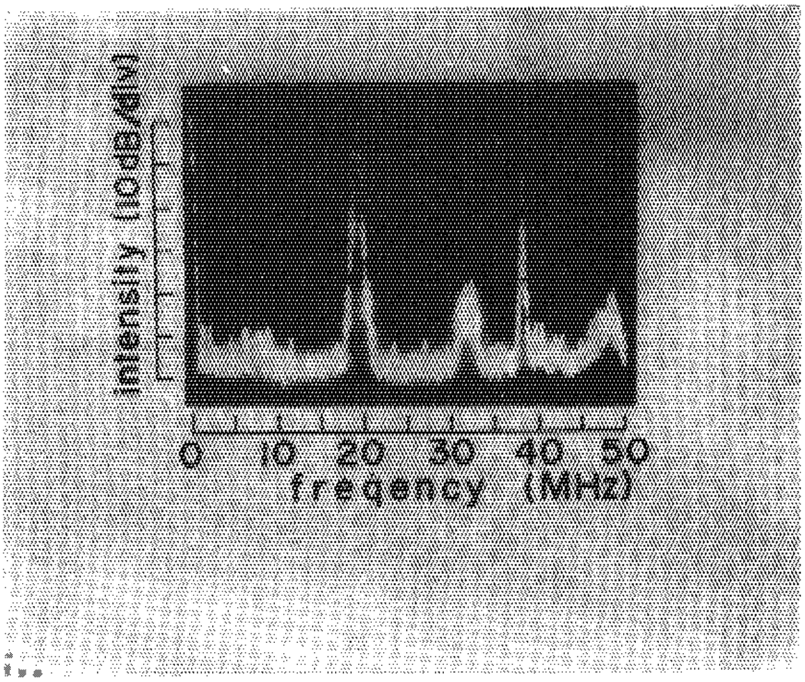

Fig. 8 Frequency spectrum obtained in JFT-2M experiment which shows an another mode at 32 MHz.

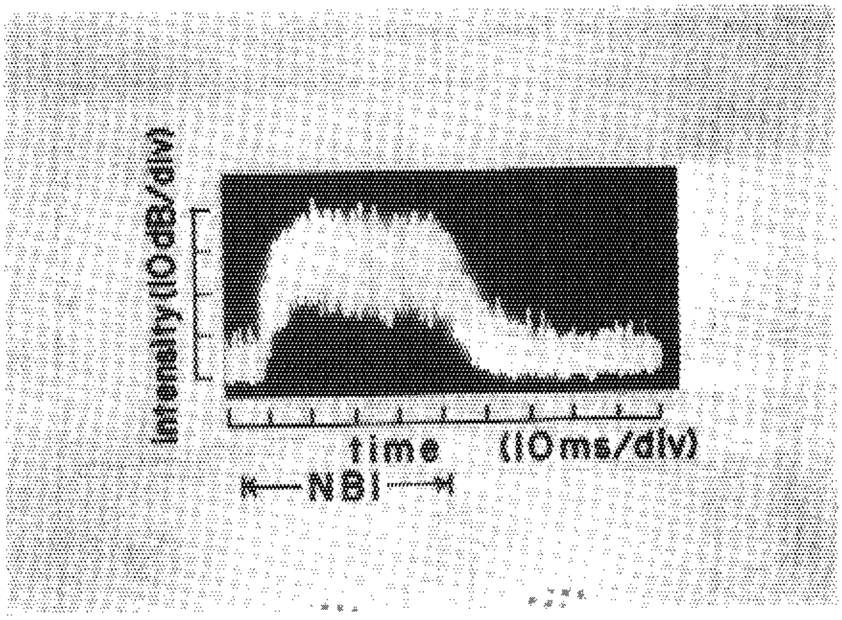

Fig. 9 Time behavior of oscillation of 32 MHz.