

電磁パルスと粒子の相互作用

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<目的>

荷電粒子をセンサーとして利用し、電磁パルスに入射させ、速度変化を評価し、「波とは何か？」について考えてみる。

<応用>

- 粒子加速（宇宙線・加速器）
- 粒子加熱（核融合など）
- プラズマ不安定と乱流（ラングミュア・ソリトン）
- プラズマ基礎（ランダウ減衰の実体）

[内容]

1. <はじめに>
波の分類、
パルスこそ普遍的、
電磁インパルスでノーベル賞を！
2. <静電パルスによる粒子加速>
粒子性パルス！
ランダウ減衰の実体に迫る・・・
3. <電磁パルスによる粒子加速>
世界初公開：サイクロトロン加速の
巨大パワー！
4. <結論>
結局、波とは何なのか？

Generation of high-power sub-single-cycle 500-fs electromagnetic pulses

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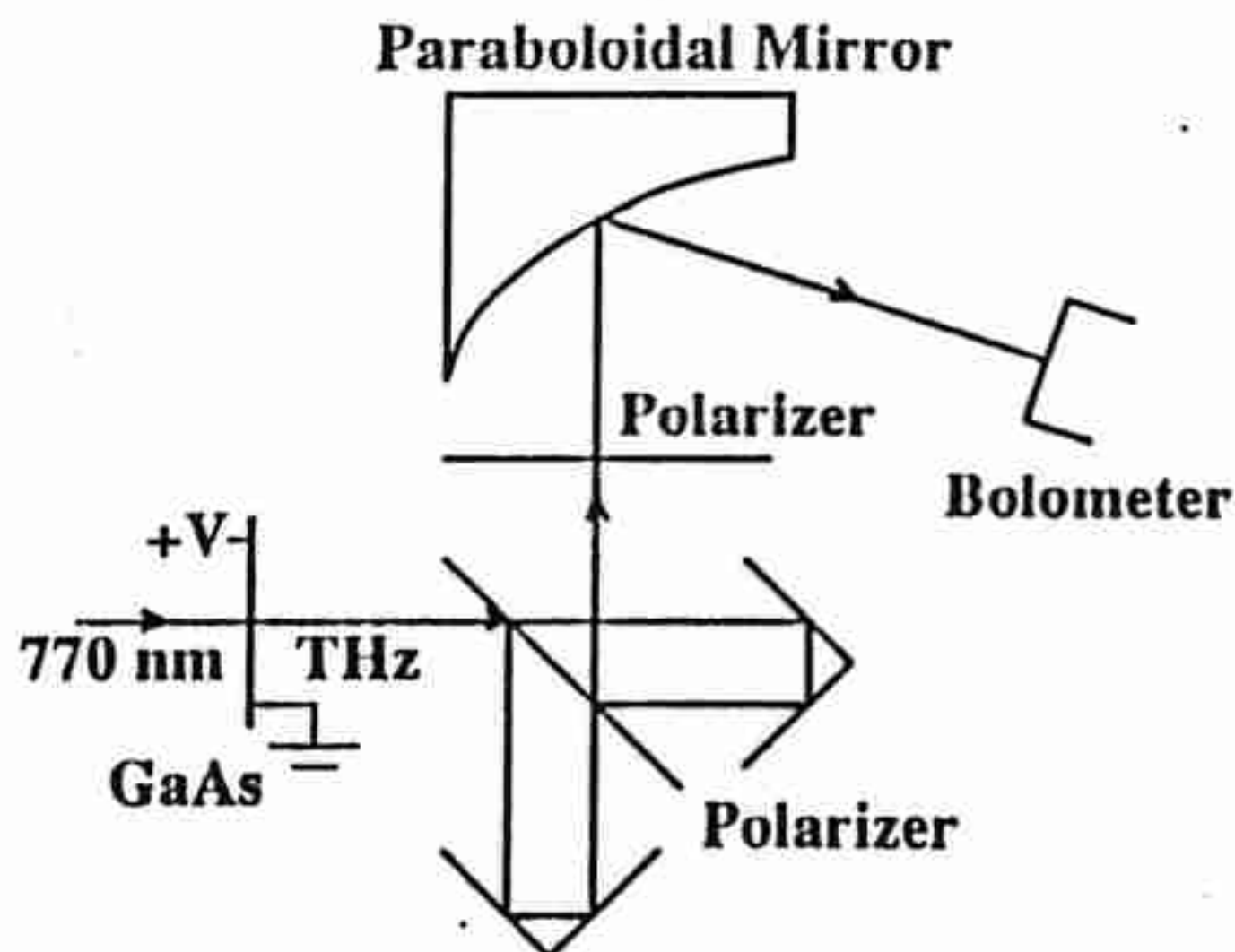


Fig. 1. Electric-field interferometer.

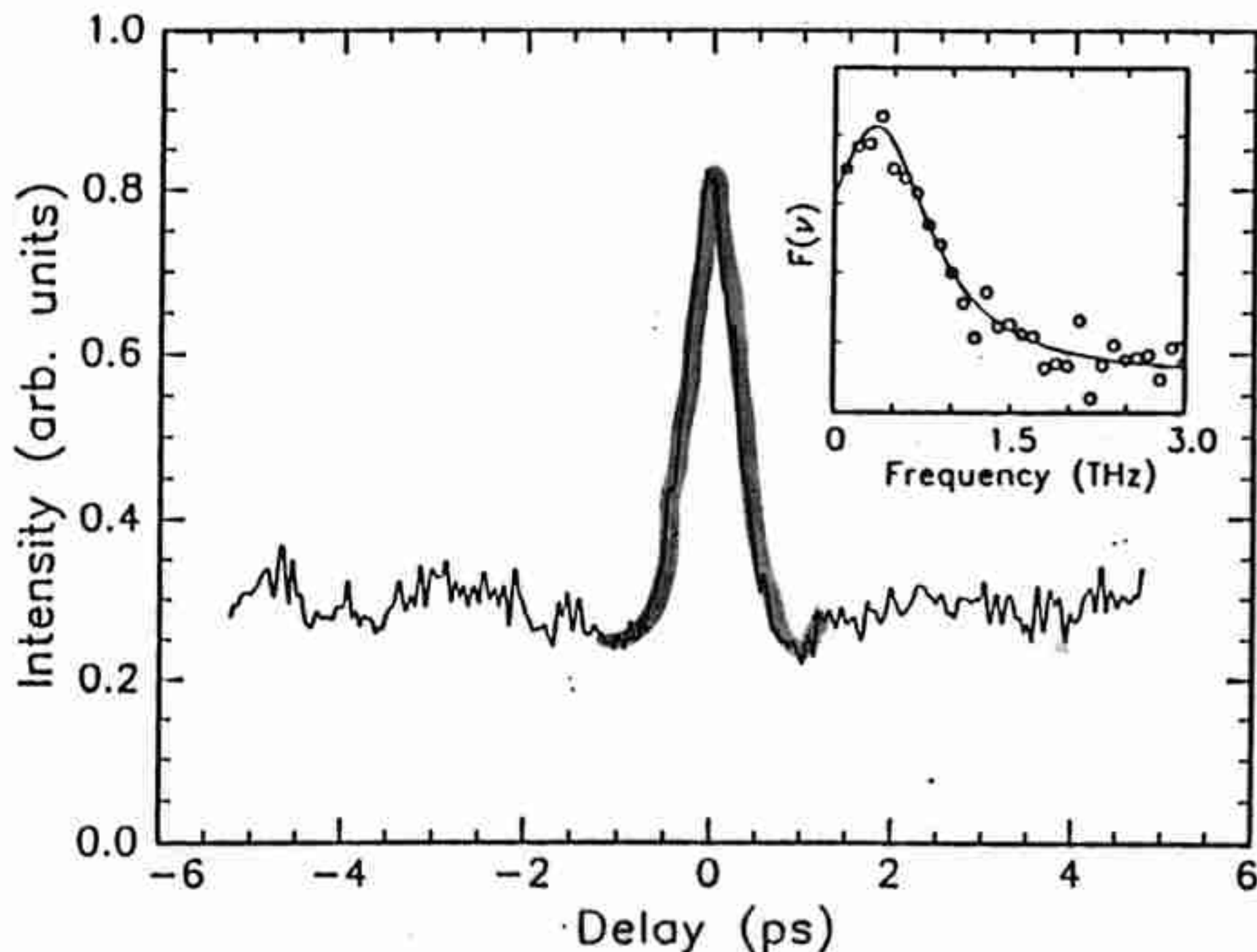


Fig. 2. Interferogram obtained by collecting the total FIR energy transmitted through the analyzing polarizer as a function of delay in one leg of the interferometer. Inset, spectrum $F(\nu)$ of the FIR pulses obtained from the interferogram.

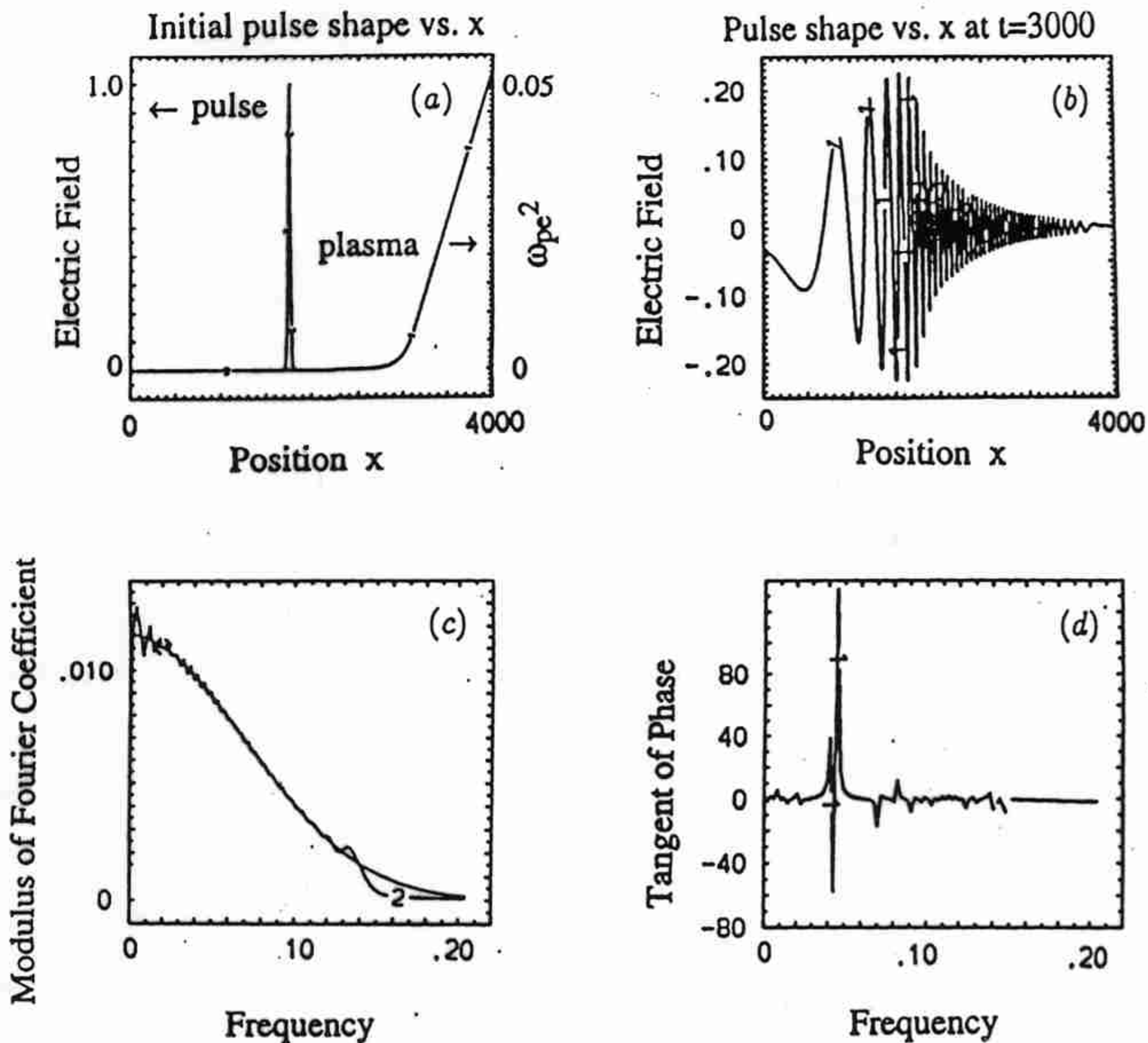


Figure 1. Pulse propagation and reflection with no density fluctuations present. (a) The initial configurations of the electromagnetic pulse and the plasma density (ω_{pe}^2 is plotted) as functions of position. (b) The reflected electromagnetic pulse against x at $t = 3000$. (c) The moduli of the Fourier coefficients of the initial (1) and reflected (2) pulses as a function of frequency/wavenumber. (d) The tangent of the phase of the complex Fourier amplitudes of the reflected pulse as a function of frequency/wavenumber.

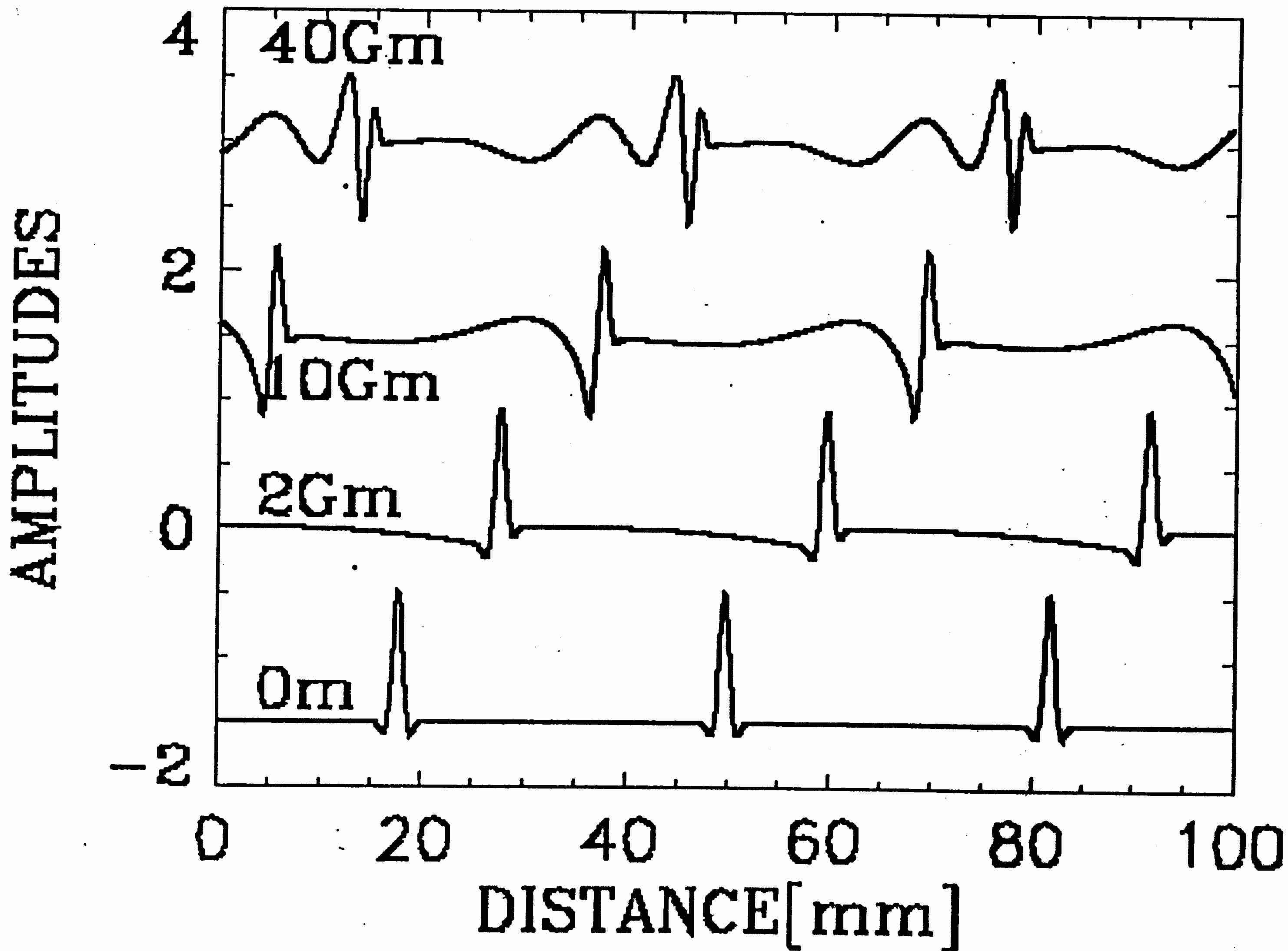
impulses in space

$$\Delta t \sim 3.3 \text{ ps}$$

10 Gbit/s

プラズマ密度 $5/\text{cm}^3$

$$\lambda_0 = 4 \text{ mm}$$



< Spectroscopy >

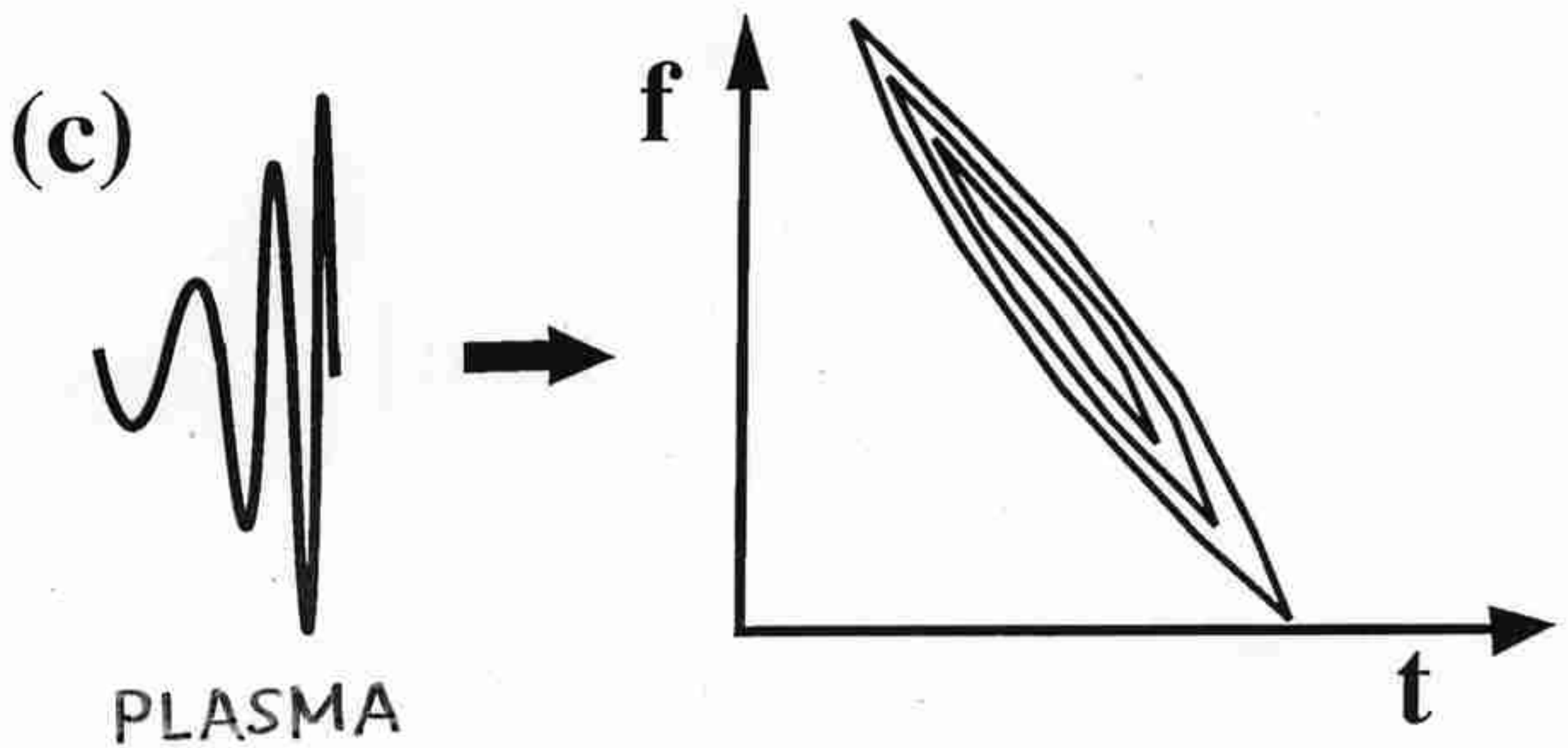
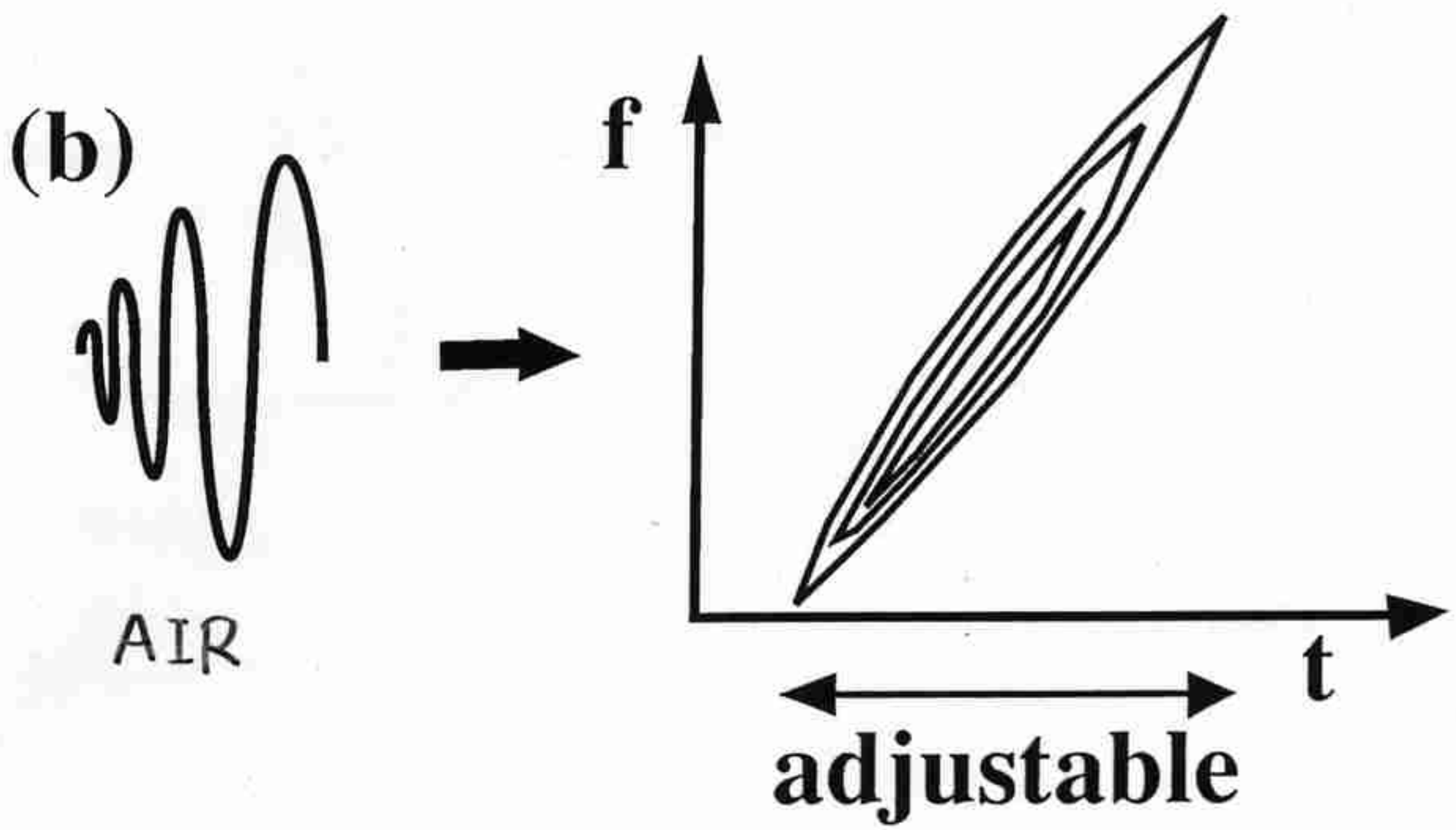
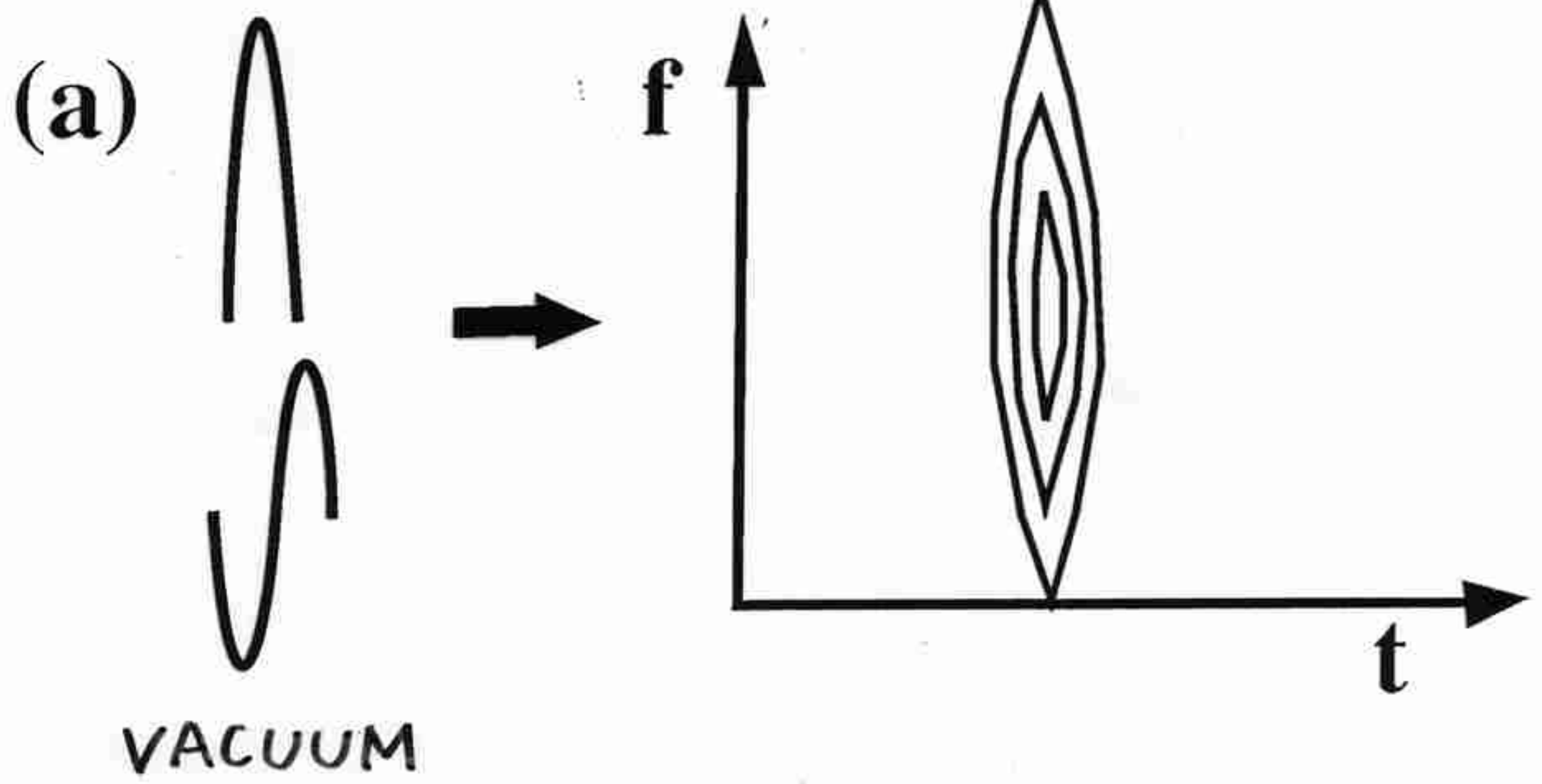
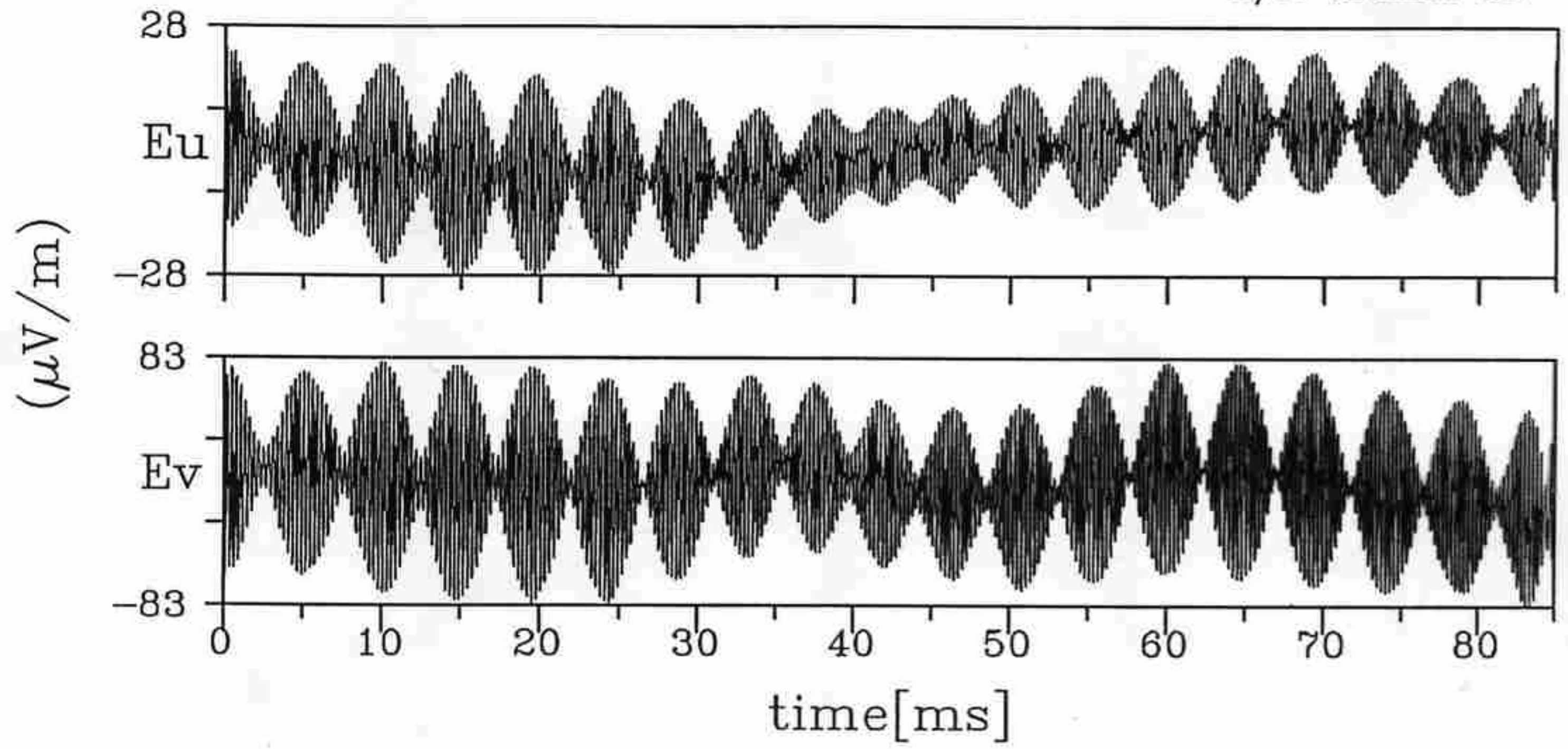


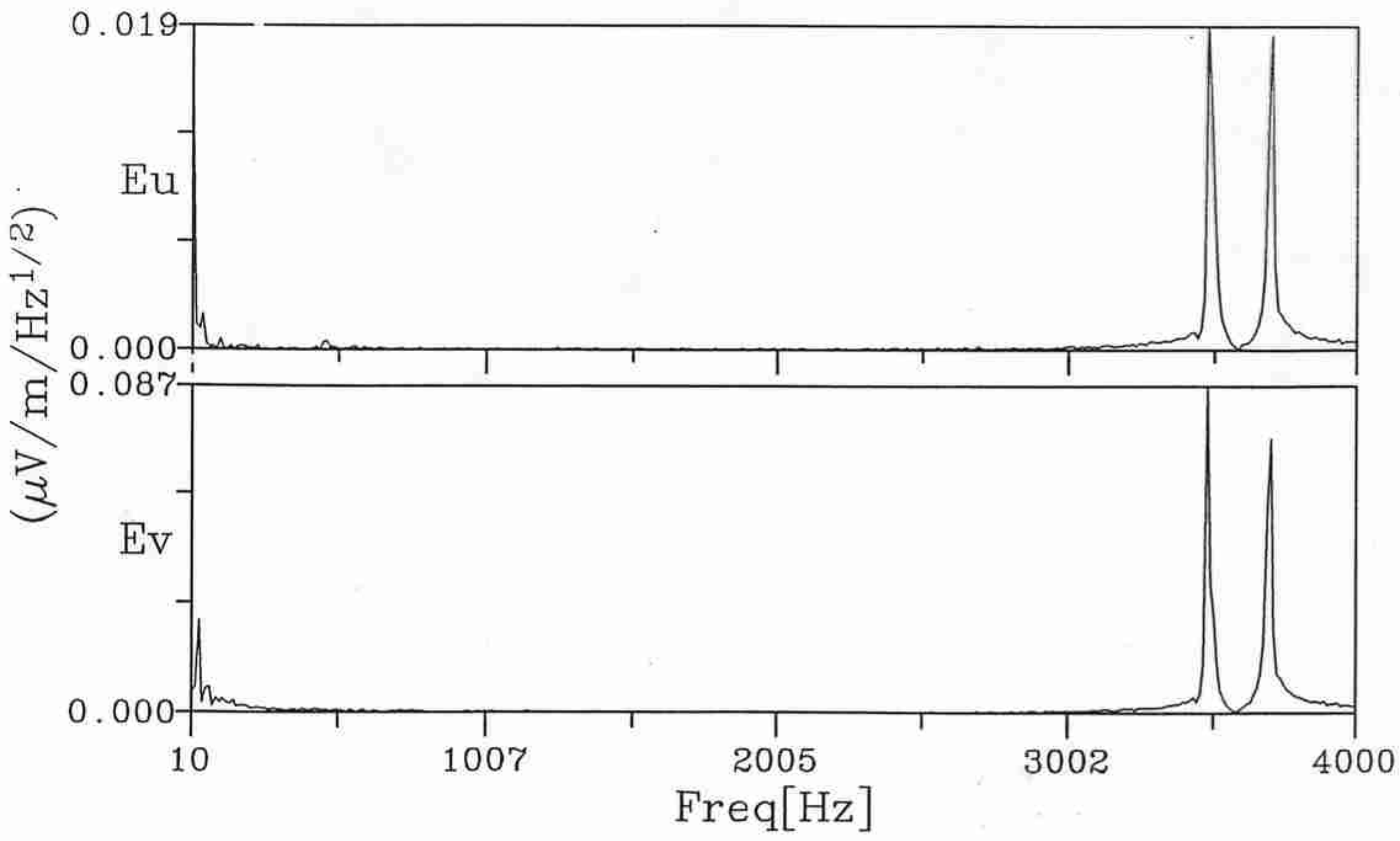
Figure 10

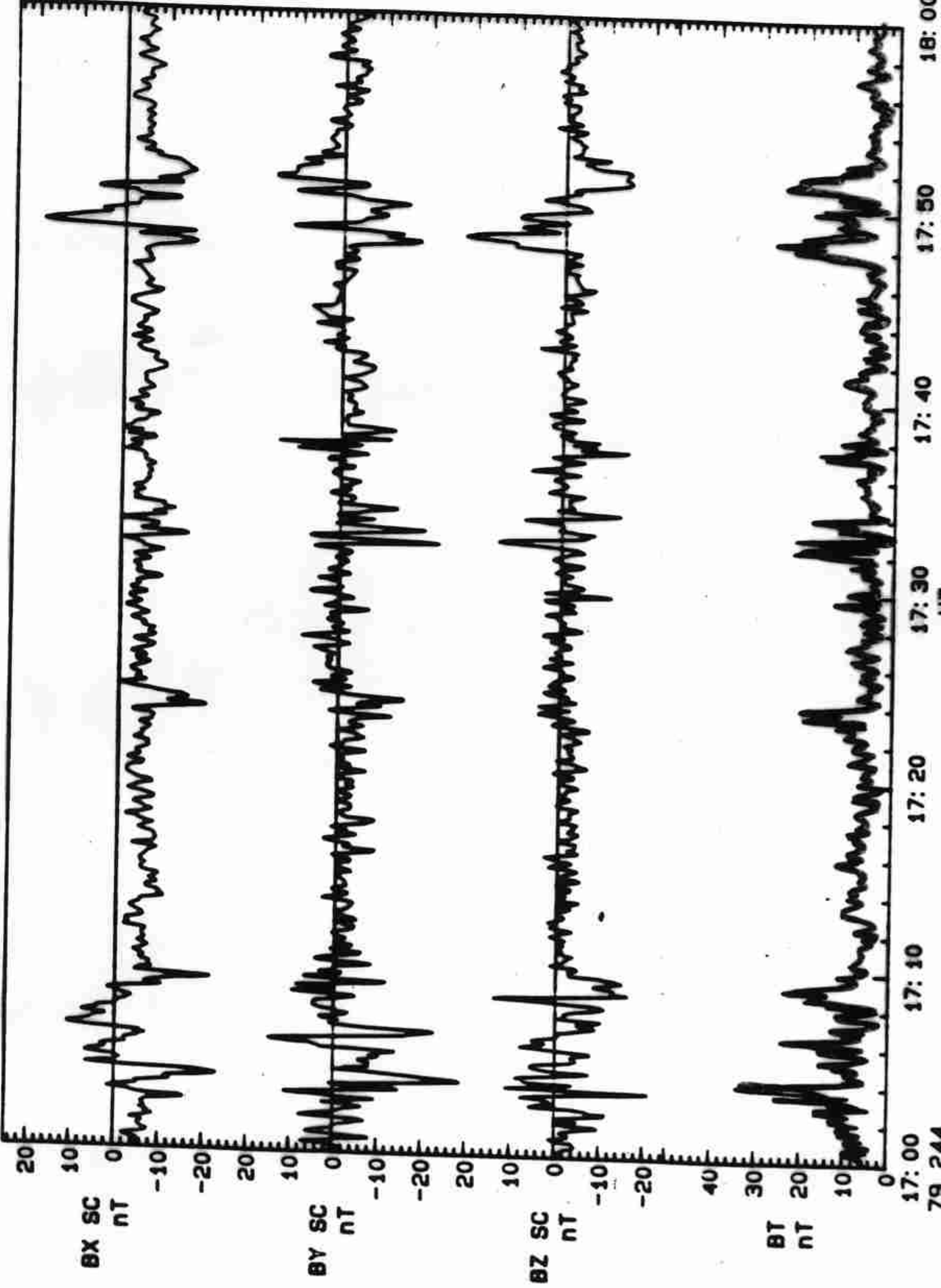
GAIN(H,H,H)
FORMAT2
MEMORY mode
calibrated
window: Rectangle
D/A trans.: ON

WAVE FORM



SPECTRUM





Pulsations [Thomsen et al. 1989]

17:00
79 244
SEP 1

EQUATION OF MOTION

$$m \frac{d^2 z}{dt^2} = qE$$

WITH

1. $E = E_0 \cos(kz - \omega t + \theta)$

SINUSOIDAL WAVE

2. $\exp[-z^2 / l^2] \cos(\omega t)$

UNIPOLAR, STATIONARY PULSE

3. $\exp[-(z - v_p t)^2 / l^2] \cos(kz - \omega t + \theta)$

PROPAGATING PULSE (DISP.=0)

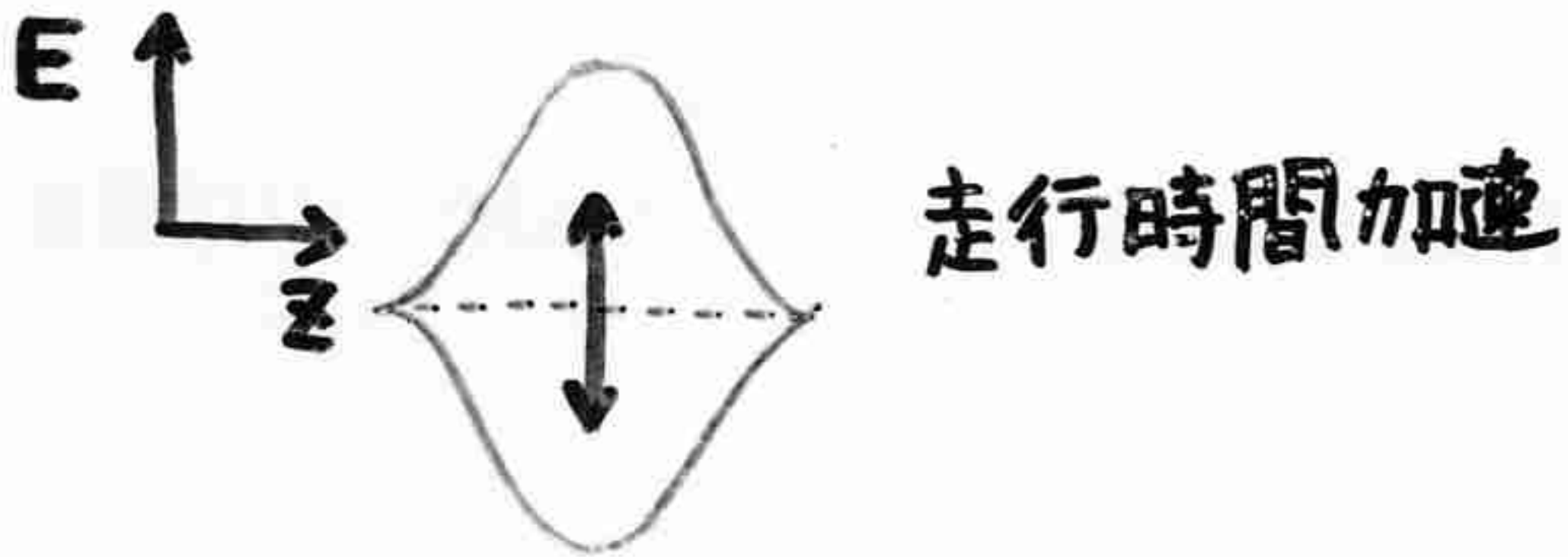
4. $\exp[-(z - v_g t)^2 / l^2(t)] \cos(kz - \omega t + \theta)$

PROPAGATING (DISP. $\neq 0$)

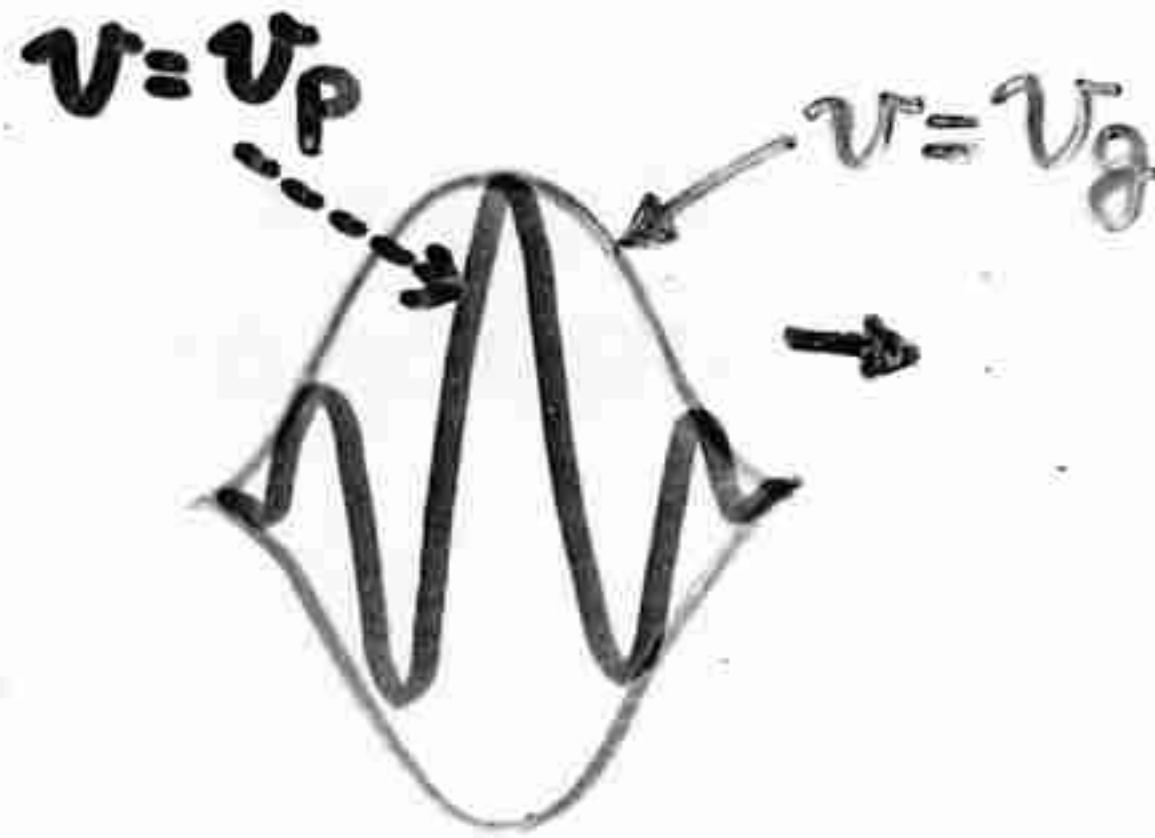
<背景>

概して定在波パルスのみ研究されてきた。

極端な分散： $v_g = 0$, $v_p = \infty$ ($k_0 = 0$)



ゼロ分散の場合も研究された。(Akimoto, 1997)

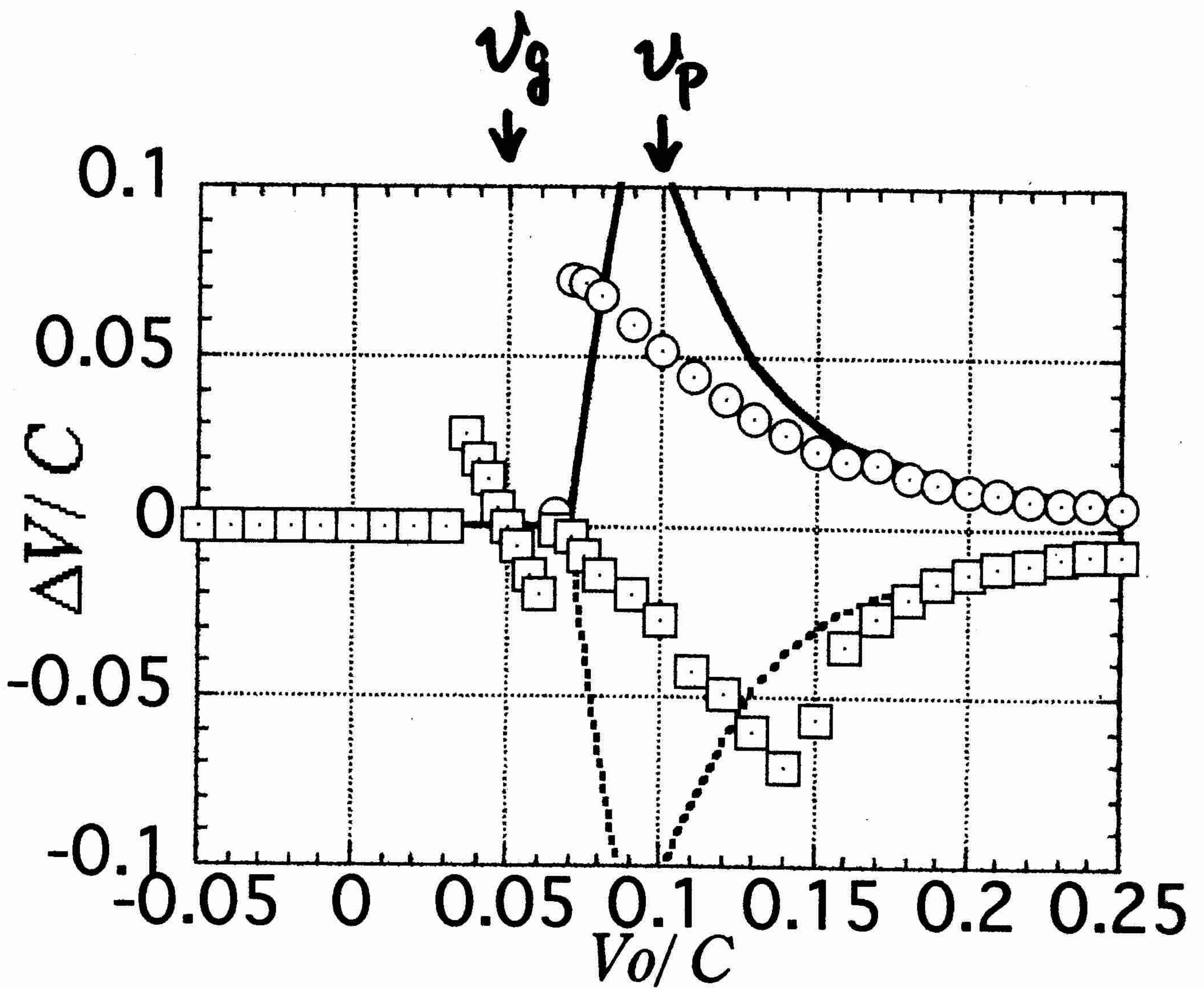


ゼロ分散： $v_g = v_p \neq 0$

今回は任意の分散に拡張した。

任意の分散： $-\infty \leq v_g, v_p \leq \infty$

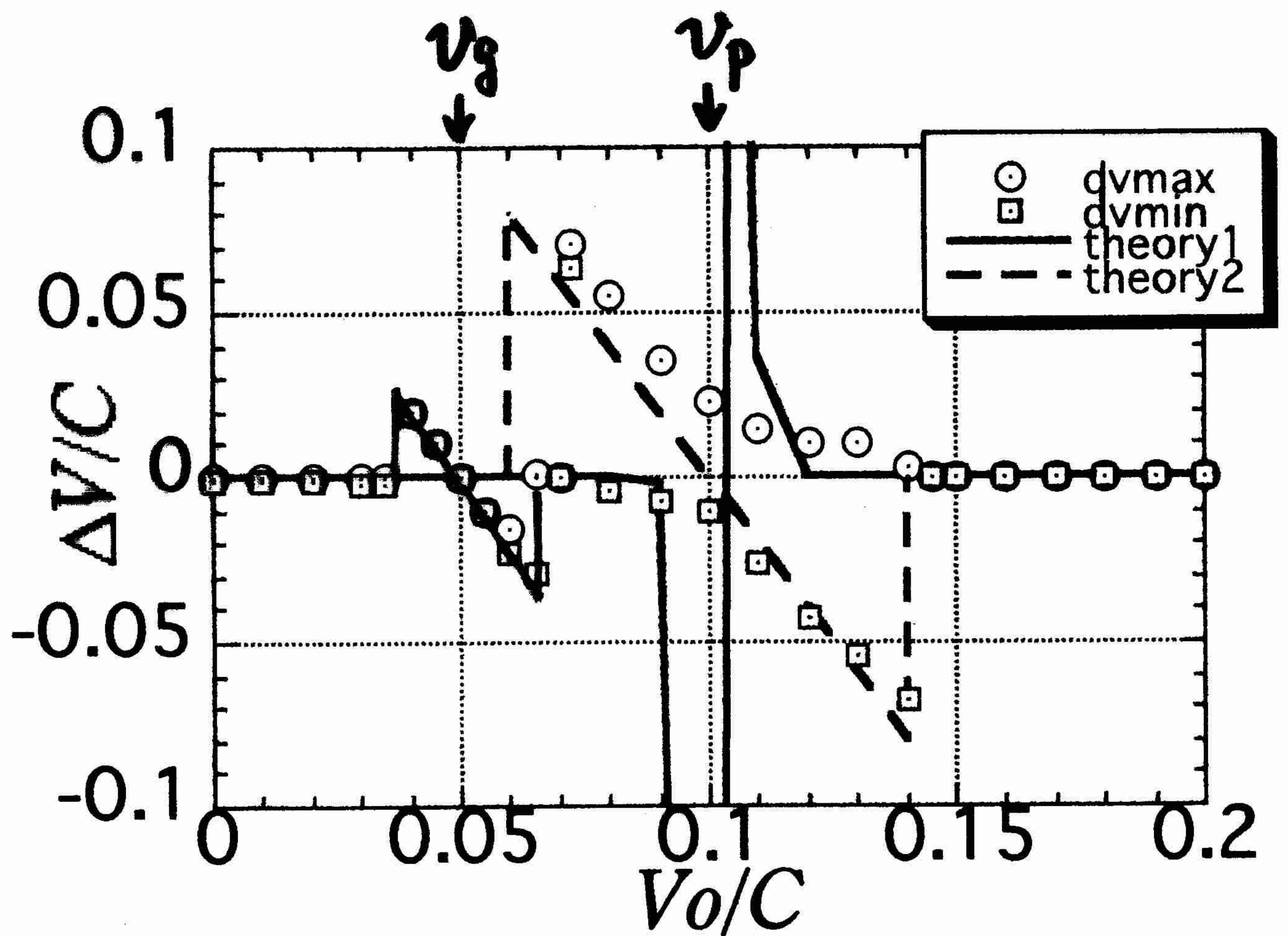
monocycle pulse



Maximum and minimum velocity shifts Δv (denoted by circles and squares respectively typically) of particles with various initial velocity v_0 after interaction with a pulse.

wave-packet

$$l_n = 2$$



v_0 dependence of velocity shifts of electrons interacting with a relatively long wavepacket. Solid curve depicts Eq.(4a), and broken curve Eq.(5b).

静電パルス

<結論>

定在波パルス：走行時間加速のみ

ゼロ分散パルス：走行時間加速と
反射

• 分散性パルスの加速機構は4種類。

1. 走行時間加速
2. Quasi-Trapping
3. 線形反射
4. 非線形反射

• 理論とテスト粒子計算は良く一致。

＜波の対称性と加速機構＞

(1次元静電波の場合)

正弦波

ランダウ減衰

パルス

- 極端な分散 (定在波) 走行時間加速のみ？
- 非分散性 走行時間加速と反射
- 分散性 走行時間加速、
Quasi-Trapping、
(加速と反射)、
Ponderomotive 反射

対称性の低下 \Rightarrow 自由度の増大

\Rightarrow 加速機構の増加

EQUATION OF MOTION AND ITS SOLUTION

II. Electromagnetic Pulse in B

The Equation of motion is in this case

$$m \frac{\partial \gamma v}{\partial t} + mV \frac{\partial \gamma v}{\partial z} = qE + \frac{q}{c} v \times (B_0 + B).$$

The solution with initial condition $v(0)=0$ at $t=a$ is

$$v_{\pm} = \frac{i q E_{\pm} \exp(i\theta)}{2 m \gamma_0} \Delta t X_{\pm},$$

where

$$X_{\pm} = Z_1(\omega_0, t) Y(\omega_0, t) - Z_1(\omega_0, a) Y(\omega_0, a),$$

$$Z_1(\omega, t) = Z(-\omega \Delta t / 2 + i \alpha t / \Delta t),$$

$$Y(\omega, t, v) = \exp\{-i \omega \alpha t - (\alpha t / \Delta t)^2\},$$

$v_{\pm}(t) = v_x(t) \pm i \sigma v_y(t)$ = perpendicular velocity perturbation, $E_{\pm} = E_x \pm i \sigma E_y$, $\Omega = |qB / mc|$ = usual cyclotron frequency, and σ is the sign of the charge q , respectively.

The final perpendicular velocity becomes

$$v_{\perp} = \frac{\sqrt{\pi} |qE| \Delta t}{2 m \gamma_0} \left\{ \exp[-(\omega_0 + \Omega / \alpha \gamma_0)^2 \Delta t^2 / 2] \right. \\ \left. + \exp[-(\omega_0 - \Omega / \alpha \gamma_0)^2 \Delta t^2 / 2] \right. \\ \left. + 2 \cos(2\theta) \exp[-(\omega_0 + \Omega / \alpha \gamma_0)^2 \Delta t^2 / 4] \right. \\ \left. - (\omega_0 - \Omega / \alpha \gamma_0)^2 \Delta t^2 / 4 \right\}^{1/2}$$

**Final perpendicular velocities
by transit-time and cyclotron acceleration
for a plane-polarized pulse:**

$$\Delta v_{\perp} = \frac{\sqrt{\pi} |qE| \Delta t}{2 m \gamma_0} \left[e^{-\{\omega_0 + \Omega / (\alpha \gamma_0)\}^2 \Delta t^2 / 2} + e^{-\{\omega_0 - \Omega / (\alpha \gamma_0)\}^2 \Delta t^2 / 2} \right. \\ \left. + 2 \cos(2\theta) e^{-\{\omega_0 + \Omega / (\alpha \gamma_0)\}^2 \Delta t^2 / 4 - \{\omega_0 - \Omega / (\alpha \gamma_0)\}^2 \Delta t^2 / 4} \right]^{1/2}$$

with

$$\Delta t = l / (\beta v_p),$$

$$\alpha = 1 - v_0 / v_p,$$

$$\beta = (v_0 - v_g) / (v_0 - v_p).$$

**The maximum perpendicular velocity shifts can be
obtained by putting $\theta = 0$.**

$$\Delta v_{\perp} = \frac{\sqrt{\pi} |qE| \Delta t}{2 m \gamma_0} \left[e^{-\{\omega_0 + \Omega / (\alpha \gamma_0)\}^2 \Delta t^2 / 4} + e^{-\{\omega_0 - \Omega / (\alpha \gamma_0)\}^2 \Delta t^2 / 4} \right]$$

< 理論 > Linear Polarization

$$E_x(z, t) = E_0 e^{-\{(z - v_g t)/l\}^2 + i(k_0 z - \omega_0 t + \theta)}$$

走行時間加速とサイクロトロン加速

$$(\Delta v_{\perp})_{\max} = \frac{\sqrt{\pi} |qE\Delta t|}{2 m\gamma_0} \times$$

$$\left\{ e^{-(\omega_0 + \Omega/\alpha\gamma_0)^2 \Delta t^2 / 4} + e^{-(\omega_0 - \Omega/\alpha\gamma_0)^2 \Delta t^2 / 4} \right\}$$

$$\alpha = 1 - v_0 / v_p; \quad \Delta t = l / (\beta v_p); \quad \beta = (v_0 - v_g) / (v_0 - v_p)$$

Quasi-Trapping

$$\text{If } \frac{\Delta v_{\perp}}{c} = \left| \frac{qE_0}{mc\omega_0} \right| \geq |v_{z0} - v_p|/c$$

$$\text{then } \Delta v_{//} = 2(v_p - v_{z0}).$$

線形反射

$$Q T \text{ と同様 } \quad (v_g \approx v_p)$$

理論解と数値解の比較

<Parameters>

1. Phase Velocity: $V_p = 0.1c$
2. Group Velocity: $V_g = 0.05c$
3. Field Strength:

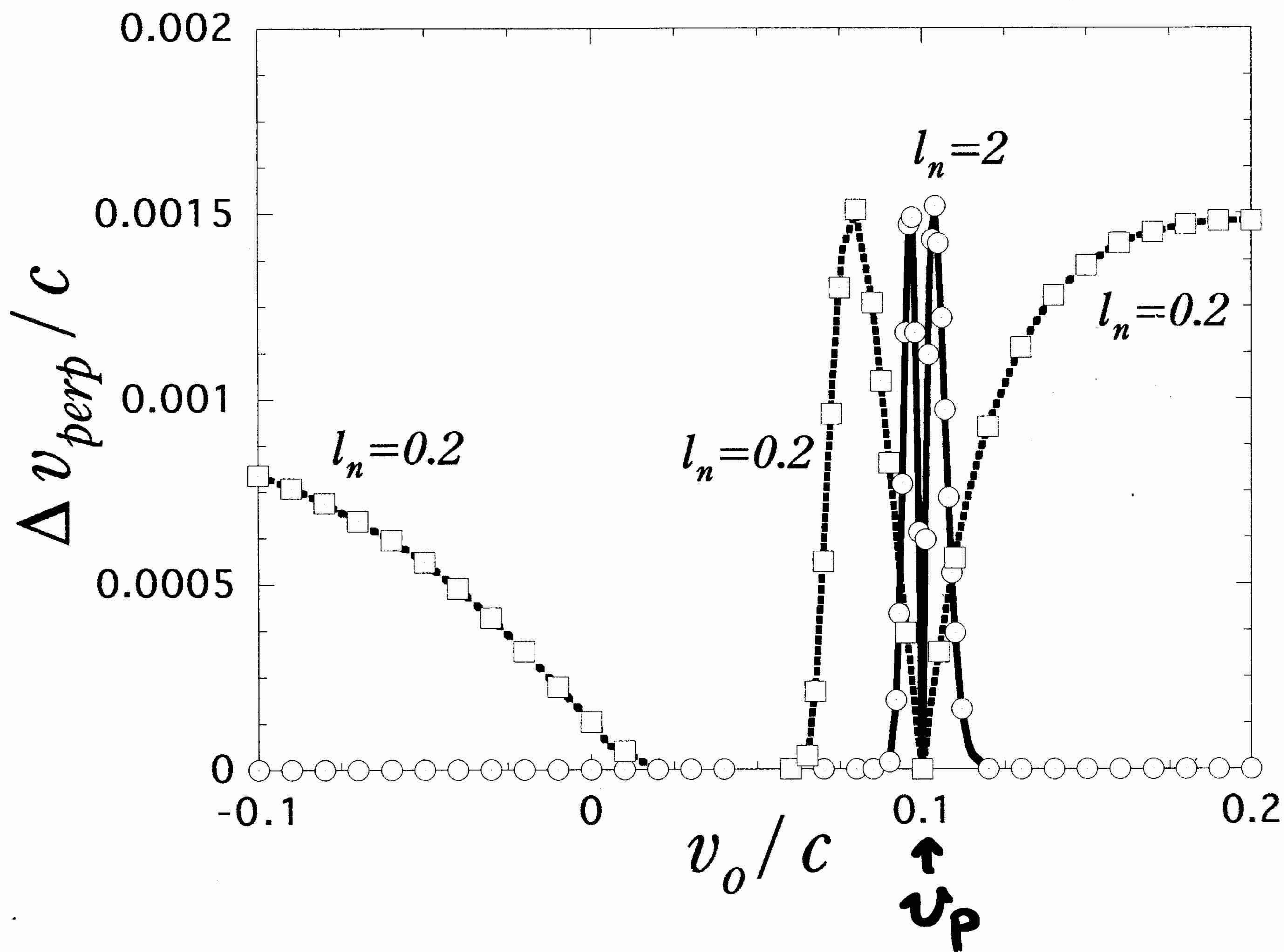
$$E_{0n} = \frac{eE_0}{mc\omega_0} = 0.03, 0.001$$

$$B_0 = 0 \text{ etc.}$$

4. Pulse Length: $l_n = 0.2$ or 2.0
Impulse
Wavepacket

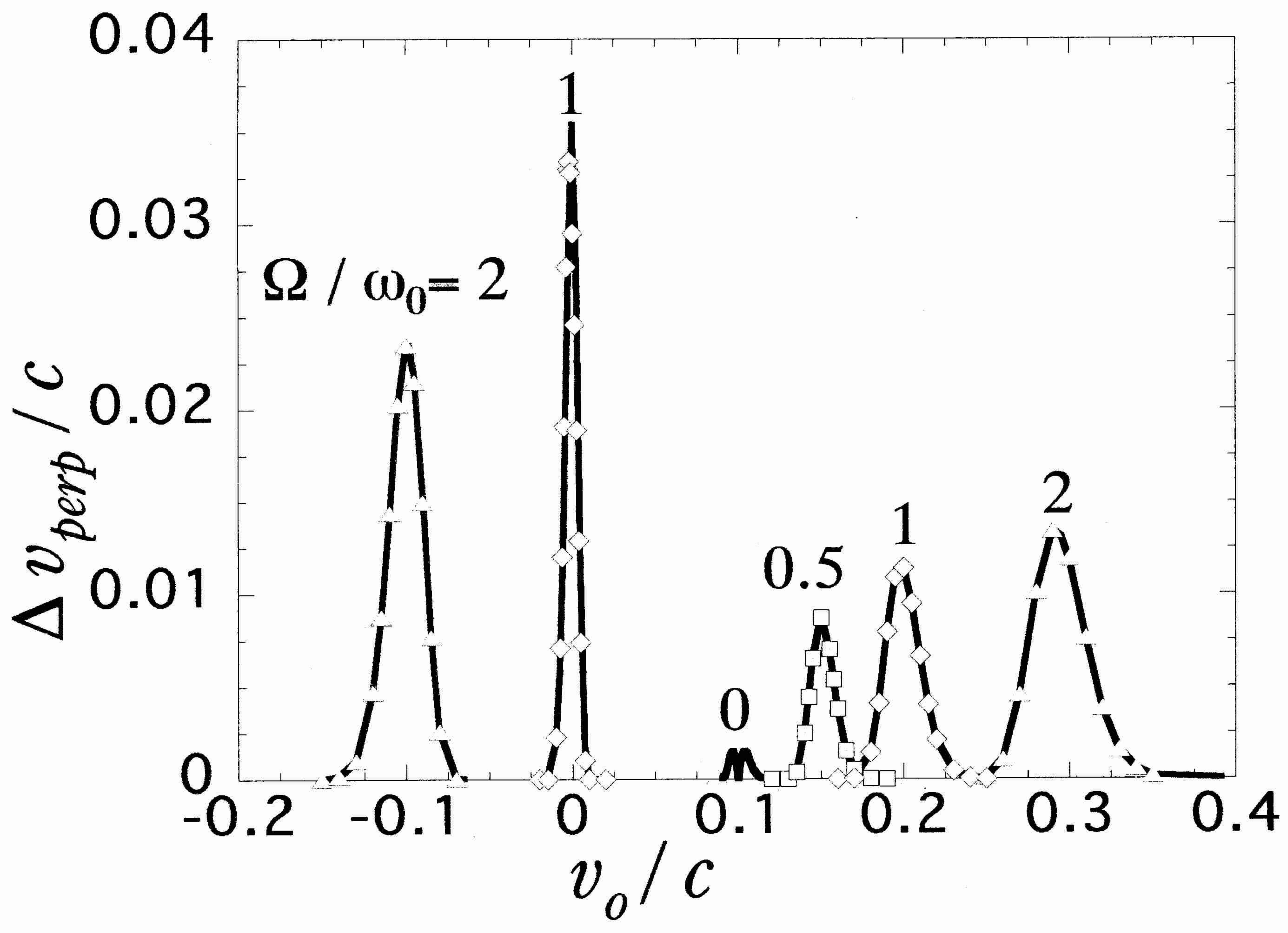
Small-amplitude EM Pulses

$$E_n = 0.001$$



B field Dependence

$$E_n = 0.001, \quad l_n = 2.0$$



<結論>

定在波パルス：走行時間加速のみ

ゼロ分散パルス：走行時間加速と反射

・分散性電磁パルスの加速機構

線形

1. 走行時間加速

2. サイクロトロン加速

非線形

3. Quasi-Trapping

4. QTによる反射

5. ponderomotive 反射

・理論とテスト粒子計算は良く一致

・電磁波の作用は静電波と本質的に同一

・波動の新たな分類方法

(粒子性パルス！)

<今後の課題>

ランダウ減衰との関係

高次元化

宇宙線や加速器などへの応用