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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P,P.O. BOX 586,34100 TRIESTE,ITALY,CABLE:CENTRATOM TRIESTE

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AUTUMN COLLEGE ON PLASMA PHYSICS

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The Electron Beam Plasma Instability: Space Observations, Theory and Simulation

(continued)

C.T. DUM

Max-Planck Institut für Extraterrestrische Physik,
Garching, Germany

These are lecture notes, intended for distribution to participants.

MAIN BUILDING STRADA COSTIERA, 11 TEL. 22401 TELEFAX 224163 TELEX 460392 ADRIATICO GUEST HOUSE VIA GRIGNANO, 9 TEL. 224241 TELEFAX 224531 TELEX 460449
MICROPROCESSOR LAB. VIA BEIRUT, 31 TEL. 224471 TELEFAX 224463 TELEX 460392 GALILEO GUEST HOUSE VIA BEIRUT, 7 TEL. 22401 TELEFAX 224559 TELEX 460392

3. Dynamics of the Wave-Beam Interaction and Quasi-linear Theory

Energy conservation:

$$-\Delta D_b = \Delta W_b + K_e + W_E \tag{1}$$

where $D_b = n_b m u^2/2$ beam drift energy density, W_b beam thermal energy, $W_E = < E^2/8\pi >$ electric field density (averaged over space), $K_e = \Delta W_e + \Delta D_e$ kinetic energy of the bulk electrons assosciated with wave motion, $K_e \approx \Delta W_e$, as $D_e = 0$ initially$\rightarrow$ $D_e \approx (\Delta D_b)^2/nmu^2$

$\omega_e t = 936$

$$8.8 \times 10^{-5} = (1.1 + 4.2 + 3.5) \times 10^{-5}$$

in units of $n_e m u^2$.

Quasilinear integral:

$$\frac{\partial N_k}{\partial t} = \int dv V_k (N_k \frac{k}{m} \frac{\partial}{\partial v} + 1) f(v)$$

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial v} \int \frac{dk}{2\pi} \frac{k}{m} V_k (N_k \frac{k}{m} \frac{\partial}{\partial v} + 1) f(v)$$

where N_k number of plasmons $V_k = M_k \delta(\omega_k - kv)$

$$m \frac{\partial f}{\partial t} = \frac{\partial}{\partial v} \frac{1}{v} \frac{\partial U_v}{\partial t}$$

$$U_v = -mv \Delta N(v, v_u)$$

$U_k = N_k \omega_k = \omega (\partial \epsilon / \partial \omega) W_k$

$U = \sum_K U_K \rightarrow \frac{L}{2\pi} \int dK\, U$

$U_v = \frac{L}{2\pi} \frac{dK}{dv} U_K$

4. Interaction with the Bulk Plasma and Mode Coupling

Nonlinear interaction between wave modes:

a.) **Nonlinear Landau damping**

$$\omega_k \pm \omega_{k'} - (k \pm k')v = 0, \qquad \Delta N_k = \pm \Delta N_{k'}$$

$$\frac{\partial N_k}{\partial t} = \sum_{j,k'} \int dv V_{k,\pm k'} [N_k N_{k'} \frac{k \pm k'}{m} \frac{\partial}{\partial v} + N_{k'} \pm N_k] f_j(v)$$

epo + *e* ↔ *epo*: **cancellation between Compton scattering and scattering off shielding cloud** (e - b, esc-e*. b)

epo + *i* ↔ *epo* (e - i - b) $\frac{\omega_k - \omega_{k'}}{k + k'}$

b.) **resonant mode coupling** (e - b - i fl)

$$\omega_k = \omega_{k'} \pm \omega_{k"} \qquad k = k' \pm k"$$

$\Delta N_{k'} = \pm \Delta N_{k'}$

$$\cancel{\Delta N_k \pm \Delta N_{k'} \pm \Delta N_{k"} = 0}$$

$\Delta N_k = -\Delta N_{k'}$

$$\frac{\partial N_k}{\partial t} = \sum_{k',k"} V_{k,k',k"} [N_{k'} N_{k"} \mp N_k N_{k'} - N_k N_{k"}]$$

epo ↔ *epo* + *iac*

Strong Turbulence (Zakharov 1972)

electron fluid equations :$n_e = n_0 + \delta n_e + \delta n_L$

$$\frac{\partial^2}{\partial t^2}\delta n_e + \omega_e^2 \delta n_e - \alpha v_e^2 \Delta \delta n_e + \nu_e \frac{\partial}{\partial t}\delta n_e = \nabla \cdot \frac{e}{m}\delta n_l \mathbf{E}_H$$

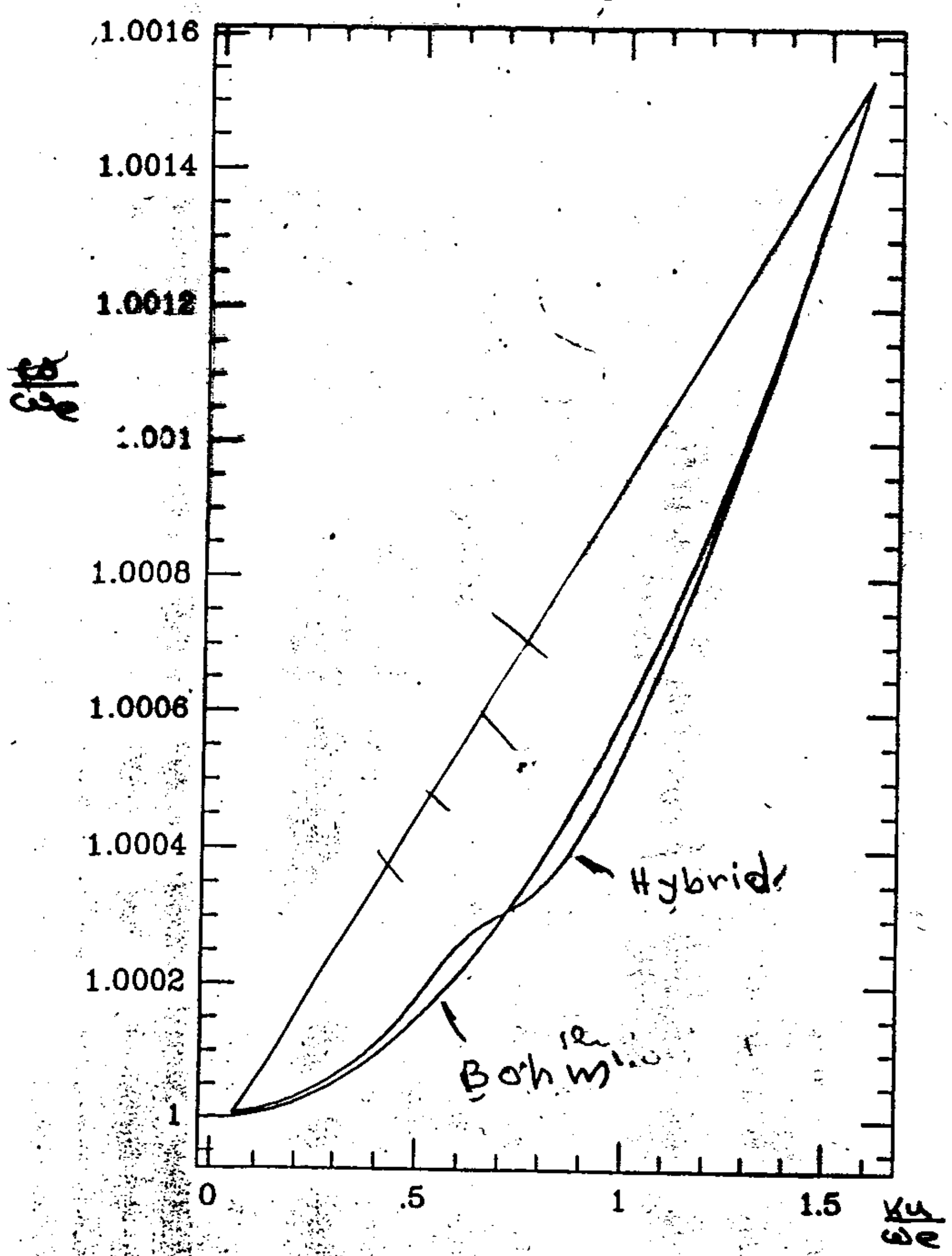
$$\nabla \cdot \mathbf{E}_H = -4\pi e \delta n_e$$

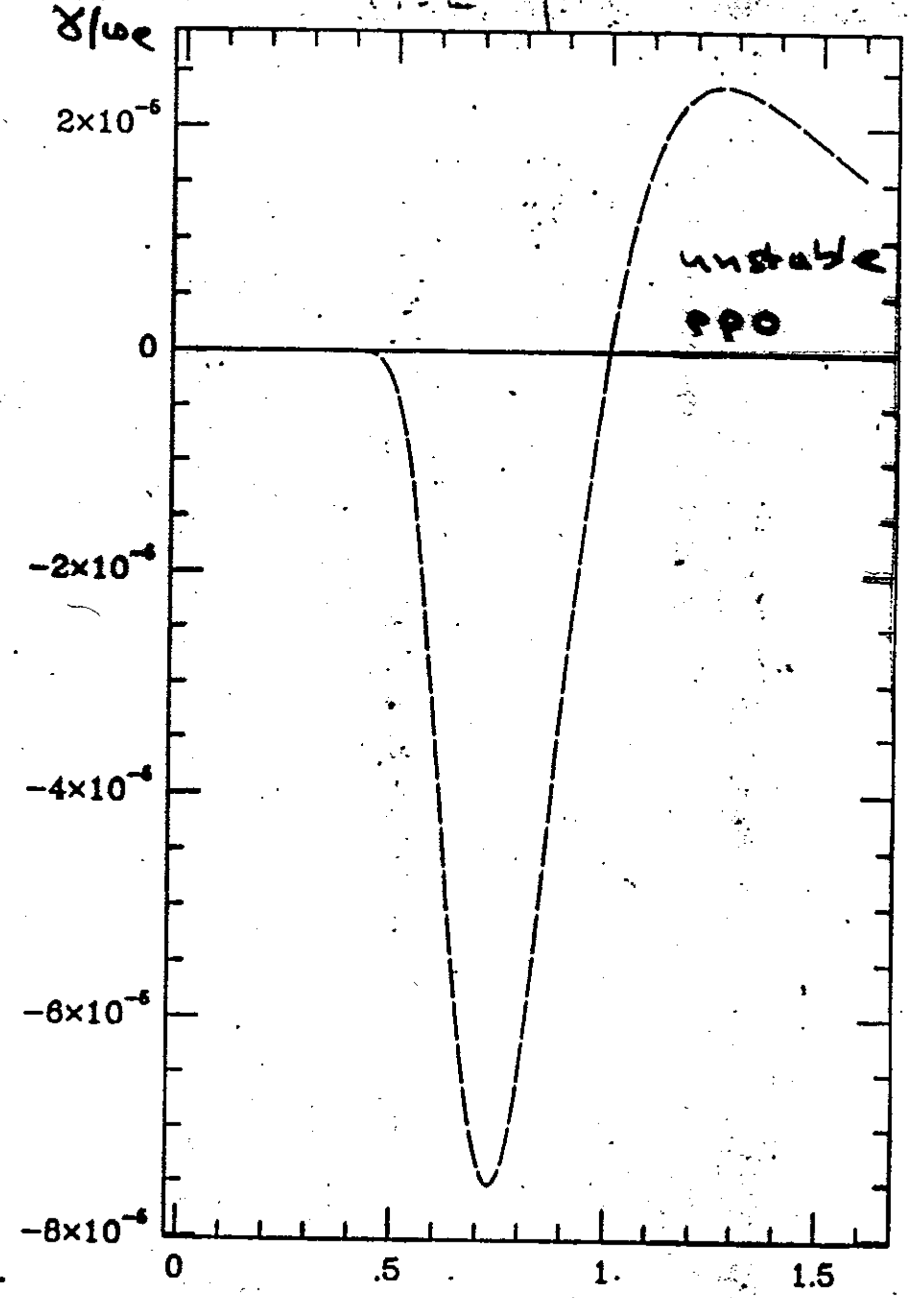
low frequency electron motion: pondermotive force

$$\delta n_L = n_0 (exp \frac{e\Phi - U}{T_e} - 1)$$

$$U = \frac{e^2}{2m\omega_e^2}\langle E_H^2 \rangle$$

ions: quasi-neutrality $\delta n_i = \delta n_L$, hydrodynamic, static or kinetic eqns include modulational instability, decay instability and NLLD by ions as special cases.



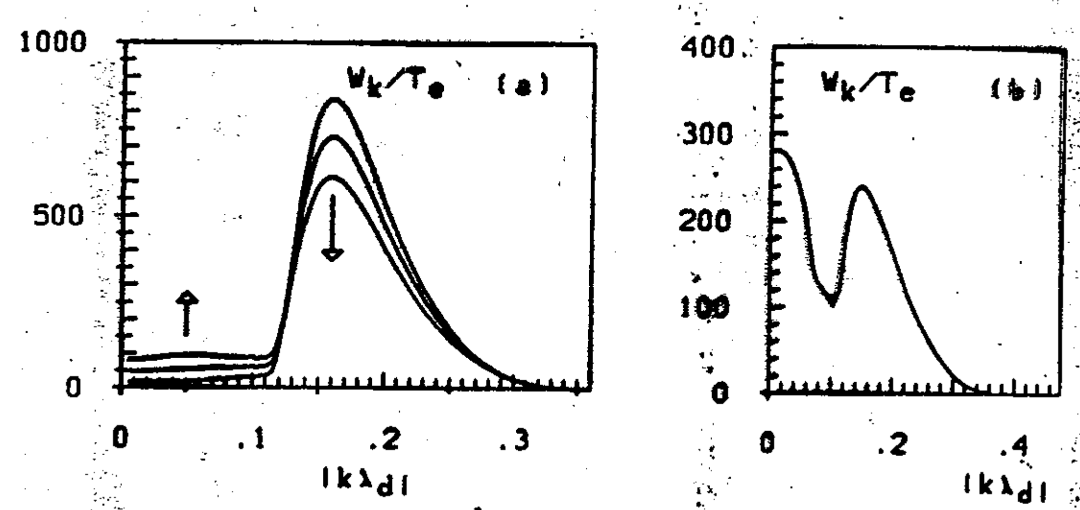


$n_b = 1.0\ E\text{-}5$ $T_b = 0.09$ $T_e = 4.0\ E\text{-}4$ ($u/v_e = 50$)

very weak beam

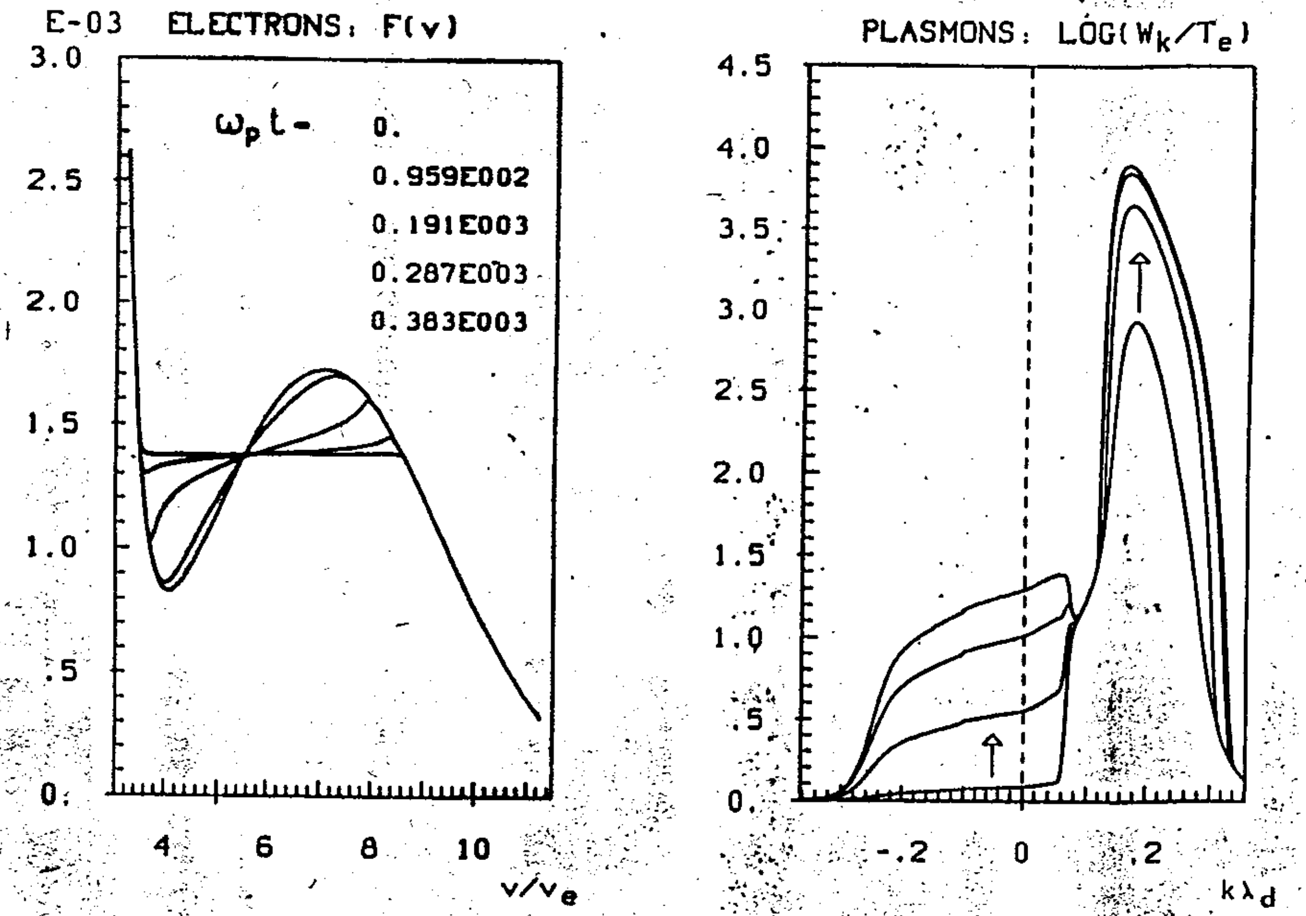
beam ignored in dispersion

$\omega_e t = 300, 600, 900$ $\qquad$ $\omega_e t = 2700$



NLLD of Langmuir waves:
buildup of condensate at $k=0$
by scattering off ions

beam is ignored in dispersion relation
and coupling coefficient
(actually only permissable for extremely weak beams
cf. prev. figure



beam included in coupling coefficients

Fig. 5 $\frac{n_b}{n_0} = 10^{-2}$ $\frac{u}{v_e} = 7.07$ $\frac{v_b}{u} = 0.33$

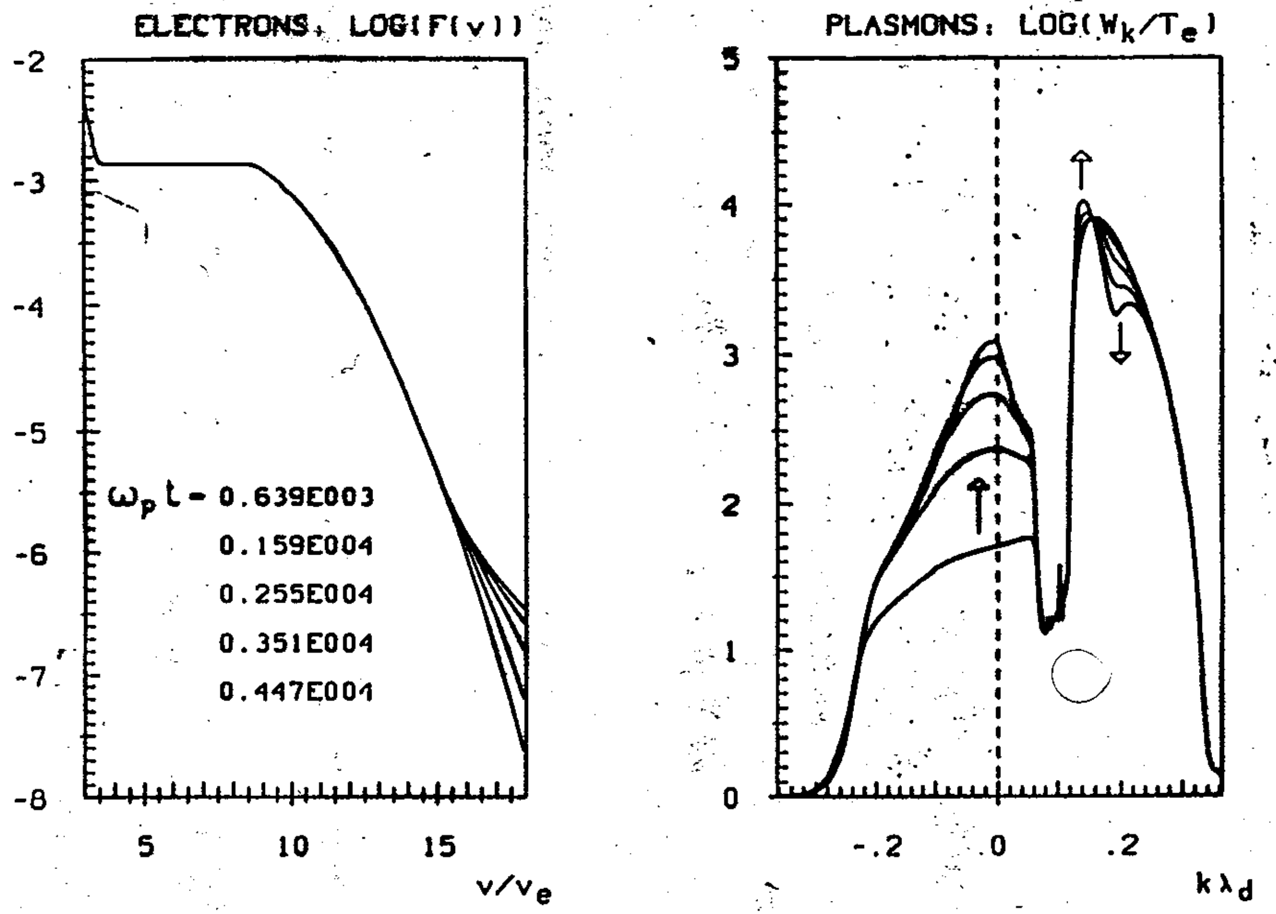
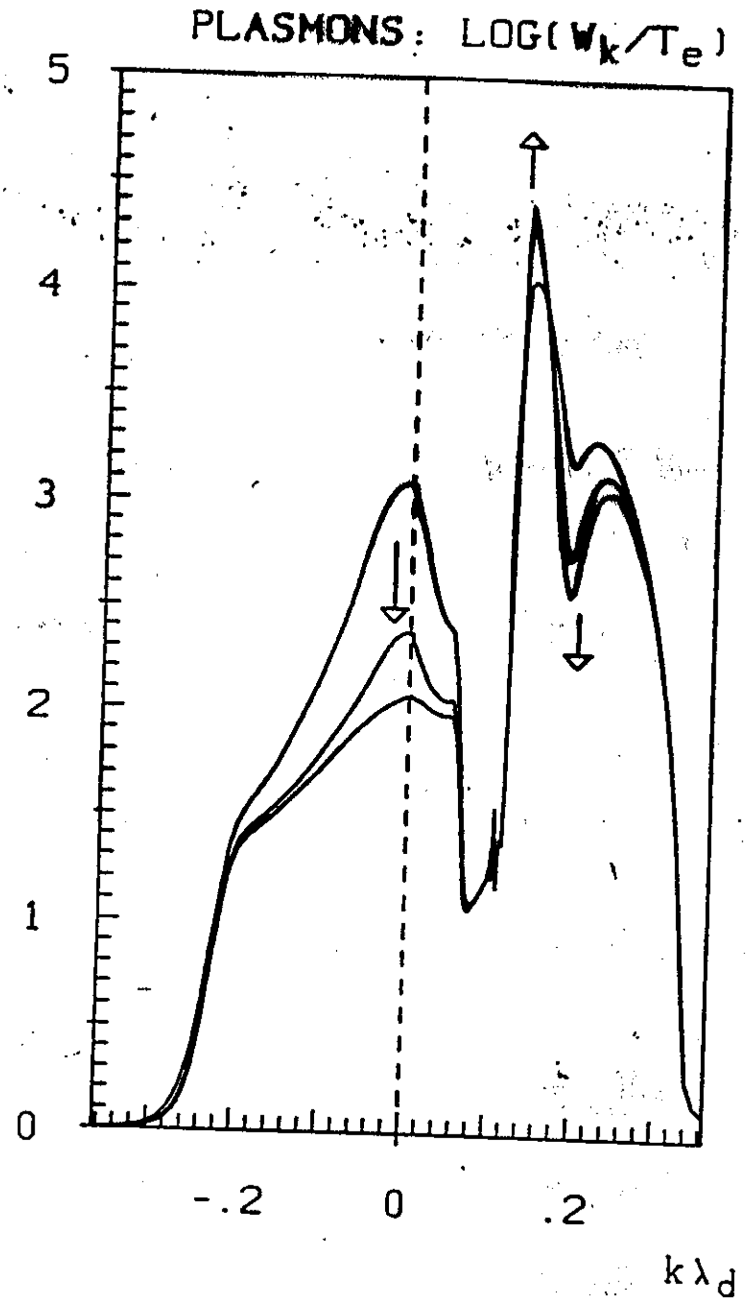


Fig. 6

contin. from Fig 5
later times
a secondary condensate of Langmuir waves is formed, e-tail acc. by fast waves

$n_b = 0.01$

$\omega_e t = 4790$
8590
11200



very late phase
of Fig 5. c
condensate at $k \approx 0$
is depleted.

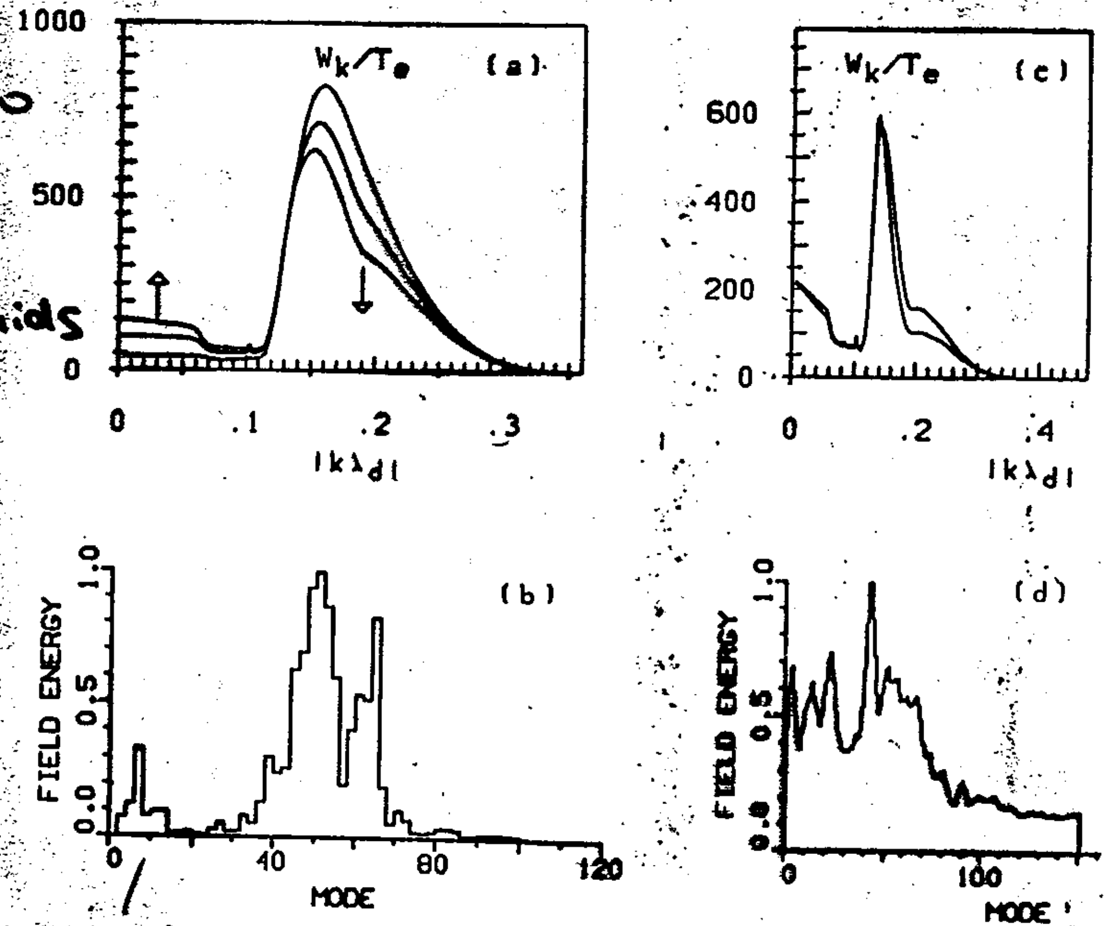
Comparison of QL+NLLD with Particle Simulation

$\omega_e t = 600, 2600$

$\omega_e t = 200, 600, 400$

QL + NLLD (i)

Muschietti, Dum 1991 Phys Fluids



Particle Simulation e + b + i

$\omega_e t = 1700$

Dum 1990 J.GR

comode (backward propagating)

$\omega_e t = 2600$

$\tau_{QL} \sim \ln(n\lambda_D)/\gamma$

$\tau^{-1} \sim 0.2 \frac{T_e}{T_i} \frac{W}{nT_e} \omega_e$

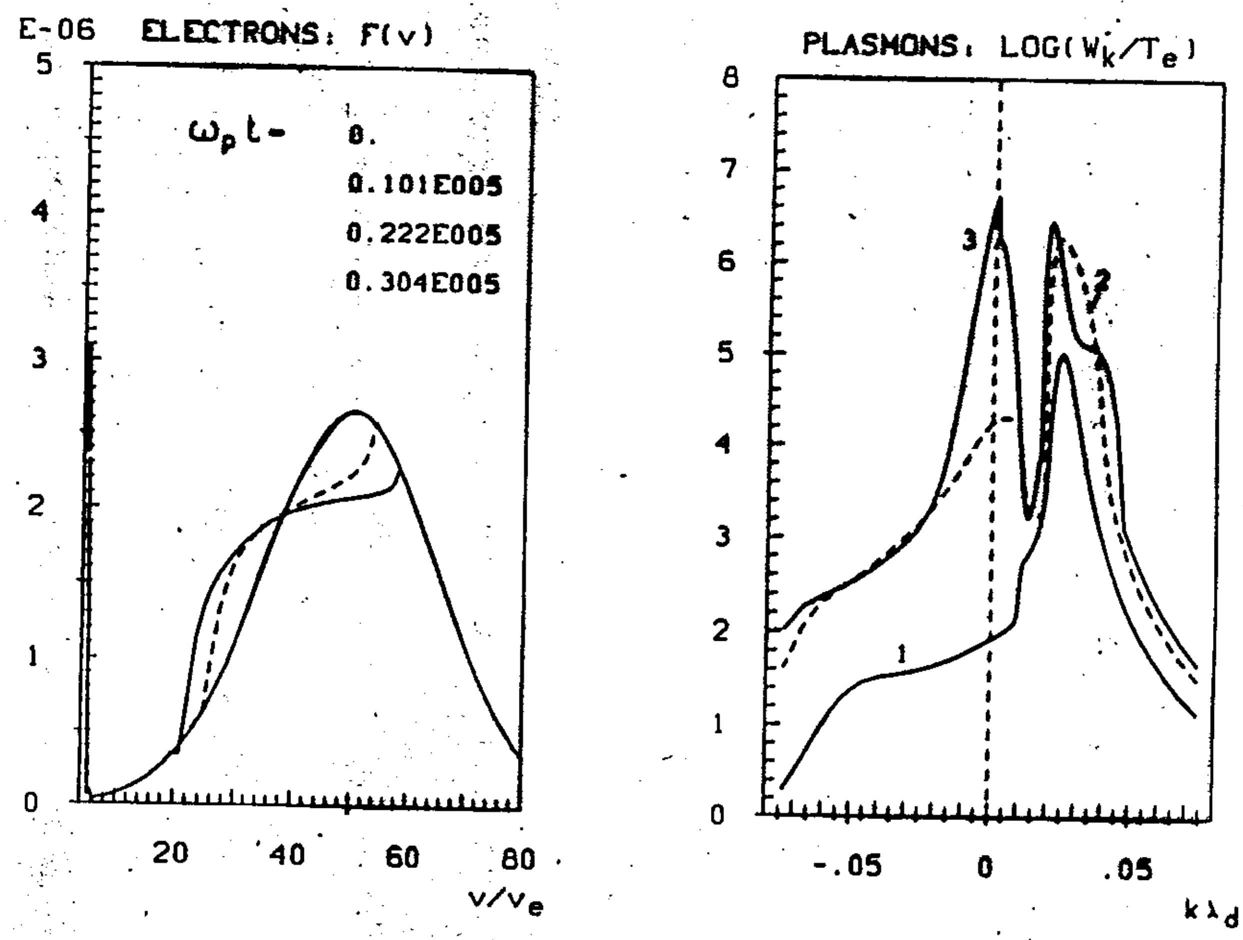
Papadopoulos, Goldstein, Smith 1974

$$\frac{n_b}{n} < 4.2 \left(\frac{v_e}{u_b}\right)^2 \left(\frac{v_b}{u_b}\right)^3$$

bump in ω dispersion relation

... weak and fast beam

$n_b \sim 10^{-4}$
$u_b/v_e = 50$
$v_b/u_b = 0.3$

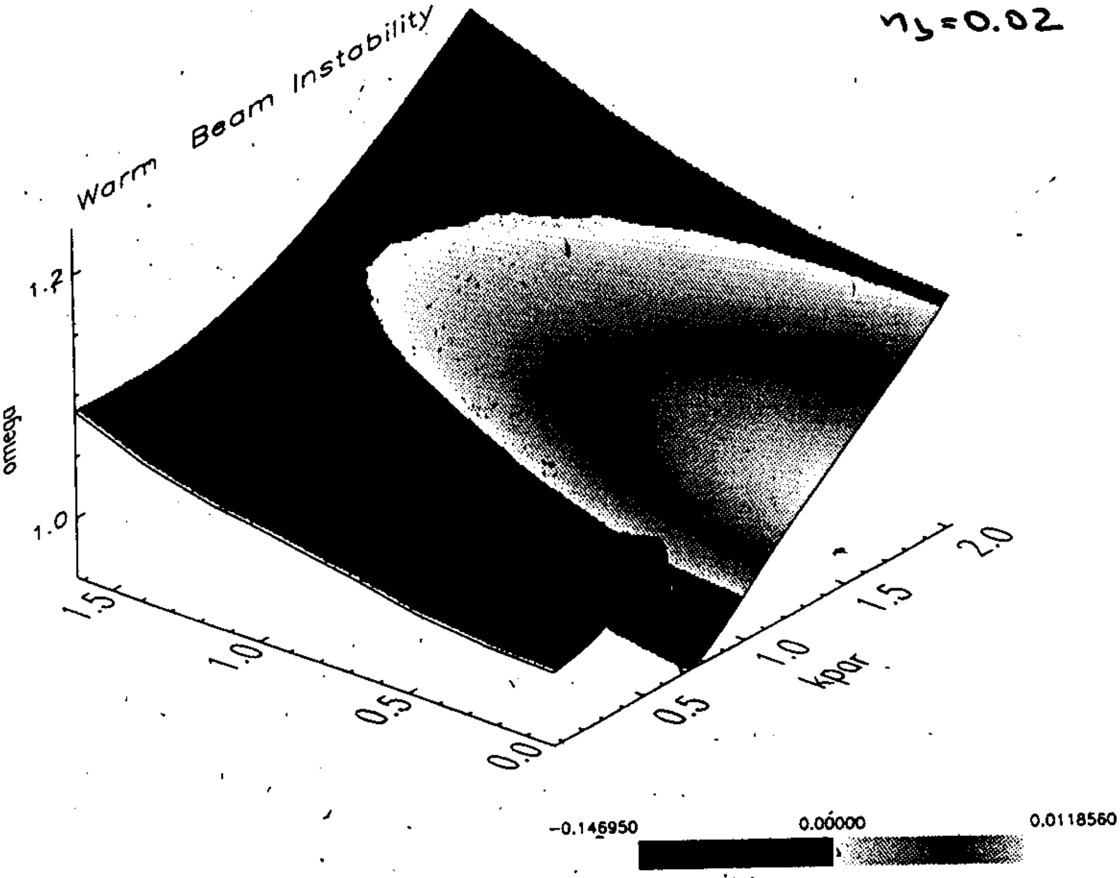


Langmuir condensate forms at 4 A D and the process stabilizes waves resonant with the beam

1 $t = 1.01 \cdot 10^4 \omega_e^{-1}$
2 $t = 2.72\ 10^4$

Tb=0.215

$n_b = 0.02$



dispersion relation
for a warm beam in unmagn.
plasma.

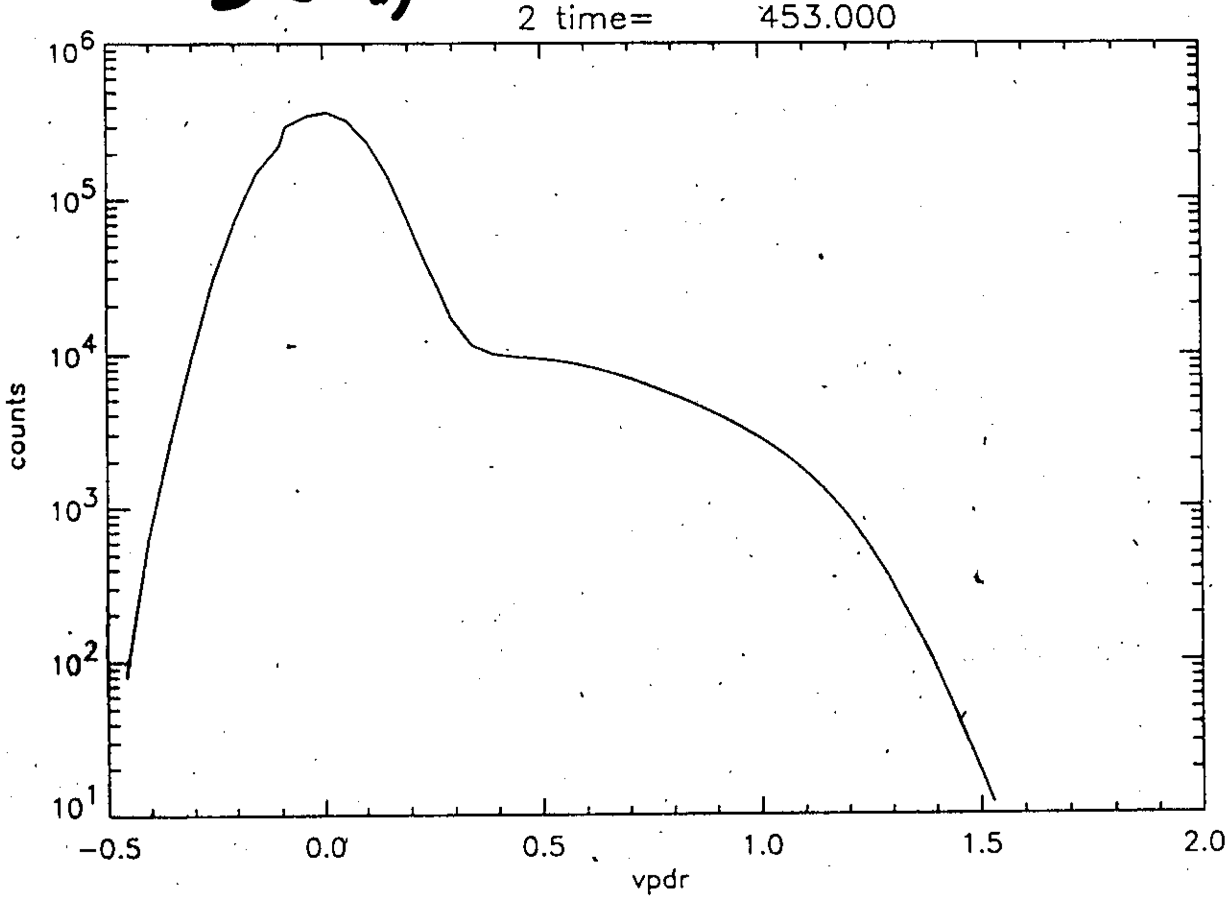
beam effect disappears
for more oblique modes,
corresponding to a larger
effective beam temperature

$T_{eff} = T_{\parallel} + T_{\perp} \tan^2\theta$

2D Kin e.b.i

$f_b(v_\parallel)$

full particle simulation



$f(v_\parallel)$

$\frac{n_b}{n} = 0.03$ $\frac{v_b}{u} = 0.05$ $\frac{v_e}{u} = 0.1$

$\Omega_{ce} = 0.05\,\omega_e$ $\frac{M}{m} = 100$ $\frac{v_i}{u} = 0.001$

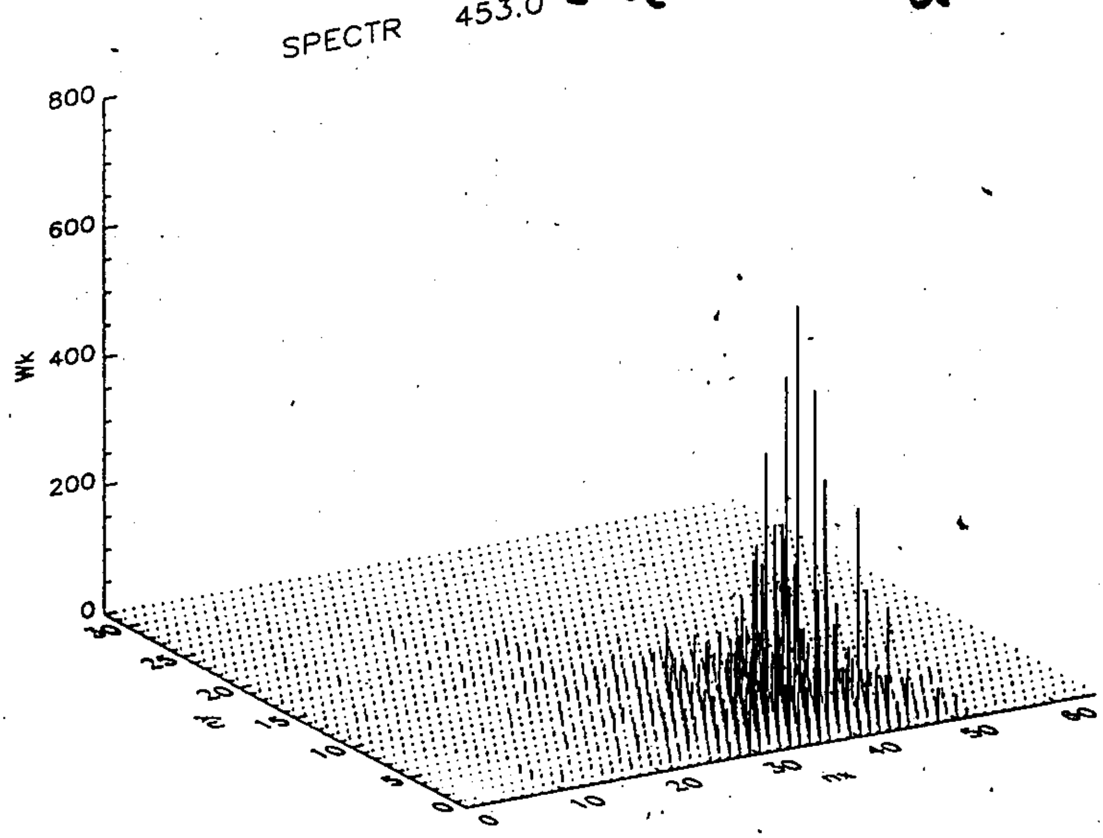
$(T_e/T_i = 10)$

accel of particles $v \ll u$ important
$f(v) \gg f_b(v)$ bulk tail $\rightarrow \frac{\partial f}{\partial v_\parallel} < 0$

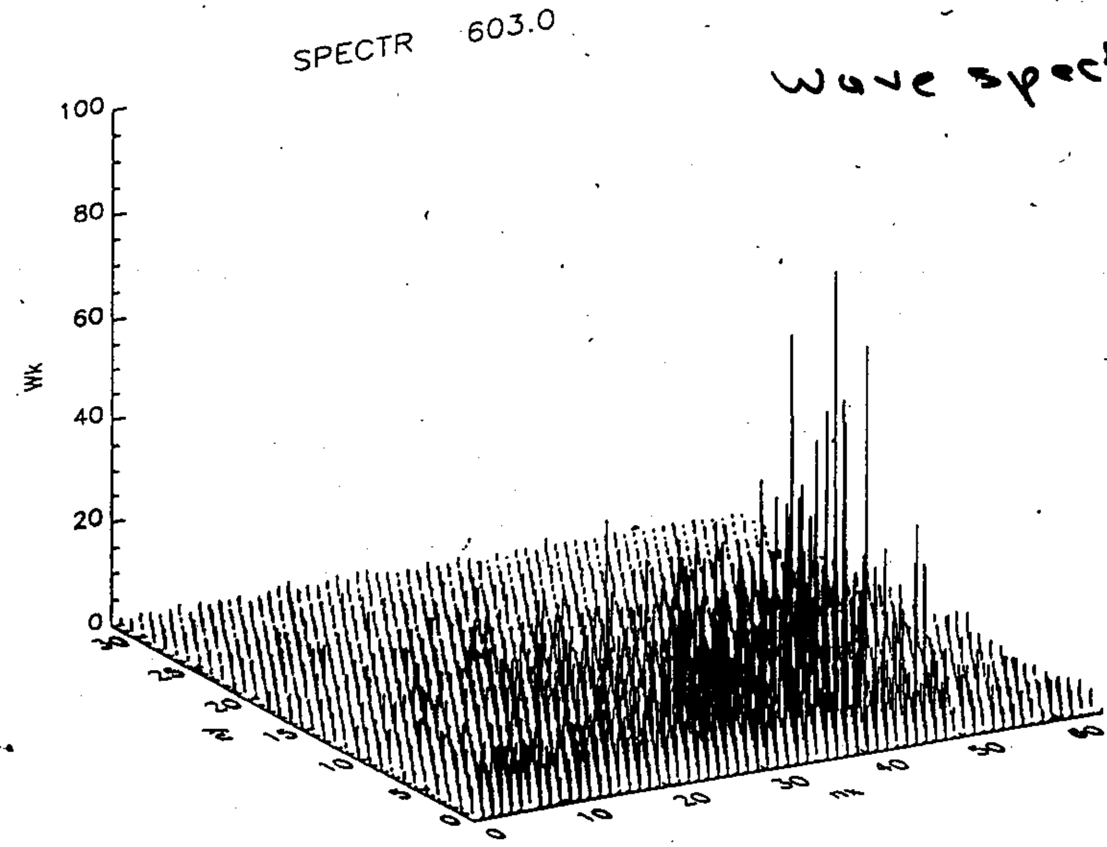
some acc $v < 0$ $\gamma < 0$
$v > u_b$

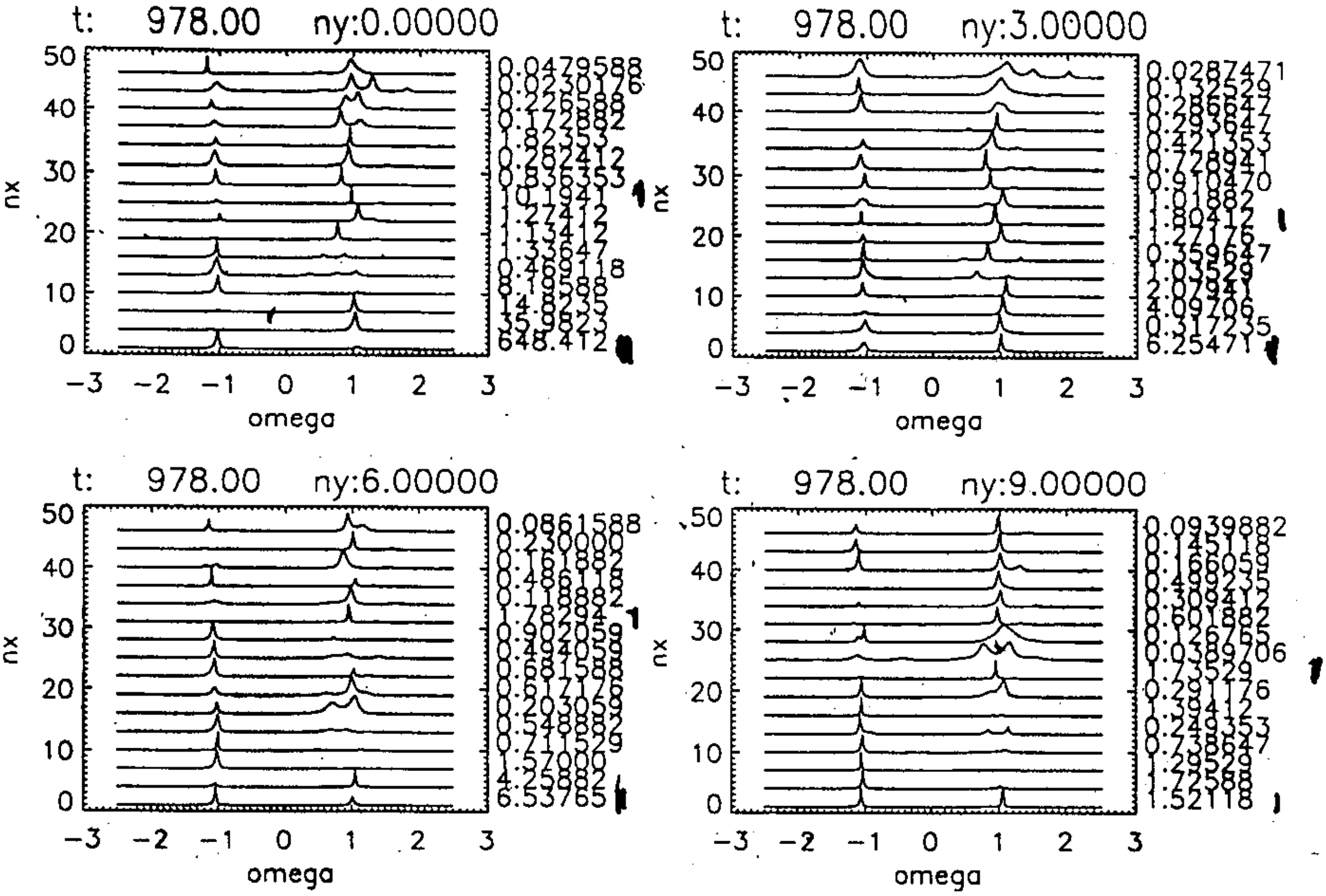
$\frac{n_b}{n} = 0.03 \quad \frac{v_b}{c} = 0.05$

$\frac{v_e}{c} = 0.1$



Wave spectrum





ω/ω_c

$n_b = 0.03$ $v_b = 0.05$ $v_e = 0.1$ $v_i = 0.001$
kin04ug.om1

2D simulation of beam excited waves, kinetic phase
generation of back scattered waves (as in 1D)
note the gaps in the forward propagating waves: they correspond to phase velocities close to the beam speed.

Reactive – Kinetic Transition

1. Linear Theory

cut off distribution 

cool beam

$\Rightarrow$ reactive instability

excitation of broad band spectrum

$0 < \omega < \omega_c \gtrsim \omega_e$ $\omega_{opt} < \omega_e$

2. observations: Lacombe et al. 1985

3. Nonlinear evolution:

a. beam broadening in reactive phase $\rightarrow$ gentle bump-on-tail kinetic

Shapiro 1963

b. single mode theories Drummond et al 1970

TRAPPING, e folding

suppression of neighboring modes Melrose 1986

c. simulation

Kainer, Dawson, Shanny, Coffey 1972

$u/v_e = 50$, n_b/n

new runs, diagnostics

$n_b/n = 1-5 \cdot 10^{-3}$ resolve reactive phase

$u/v_e = 7$ system length L $\gg$

Conclusion: 1. early reactive phase

Q.L.: ω, γ, fb short

2. Late reactive phase

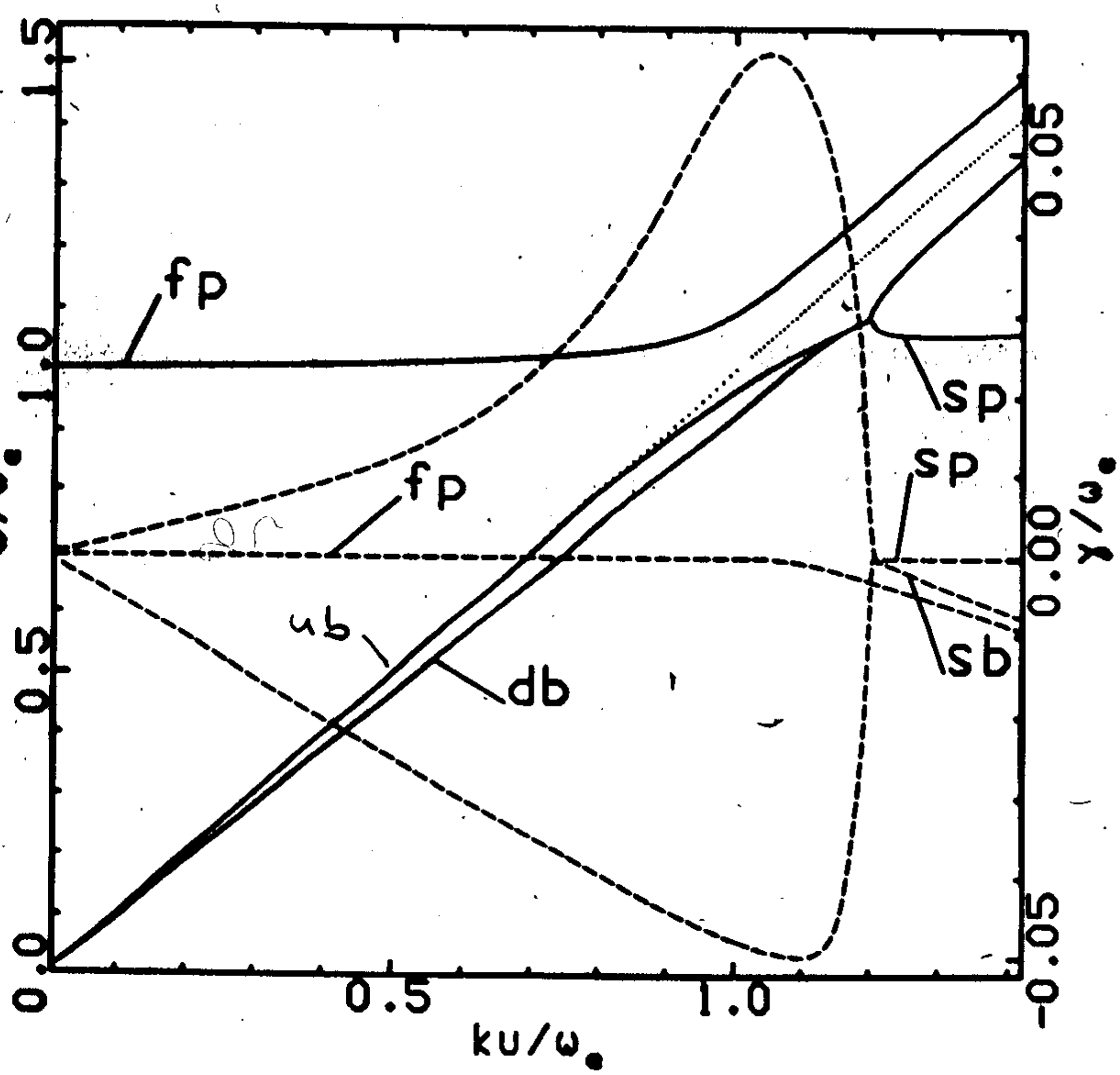
N.L.: trapping

still many modes $\rightarrow$ phase mixing

3. Kinetic Phase

Q.L gentle bump

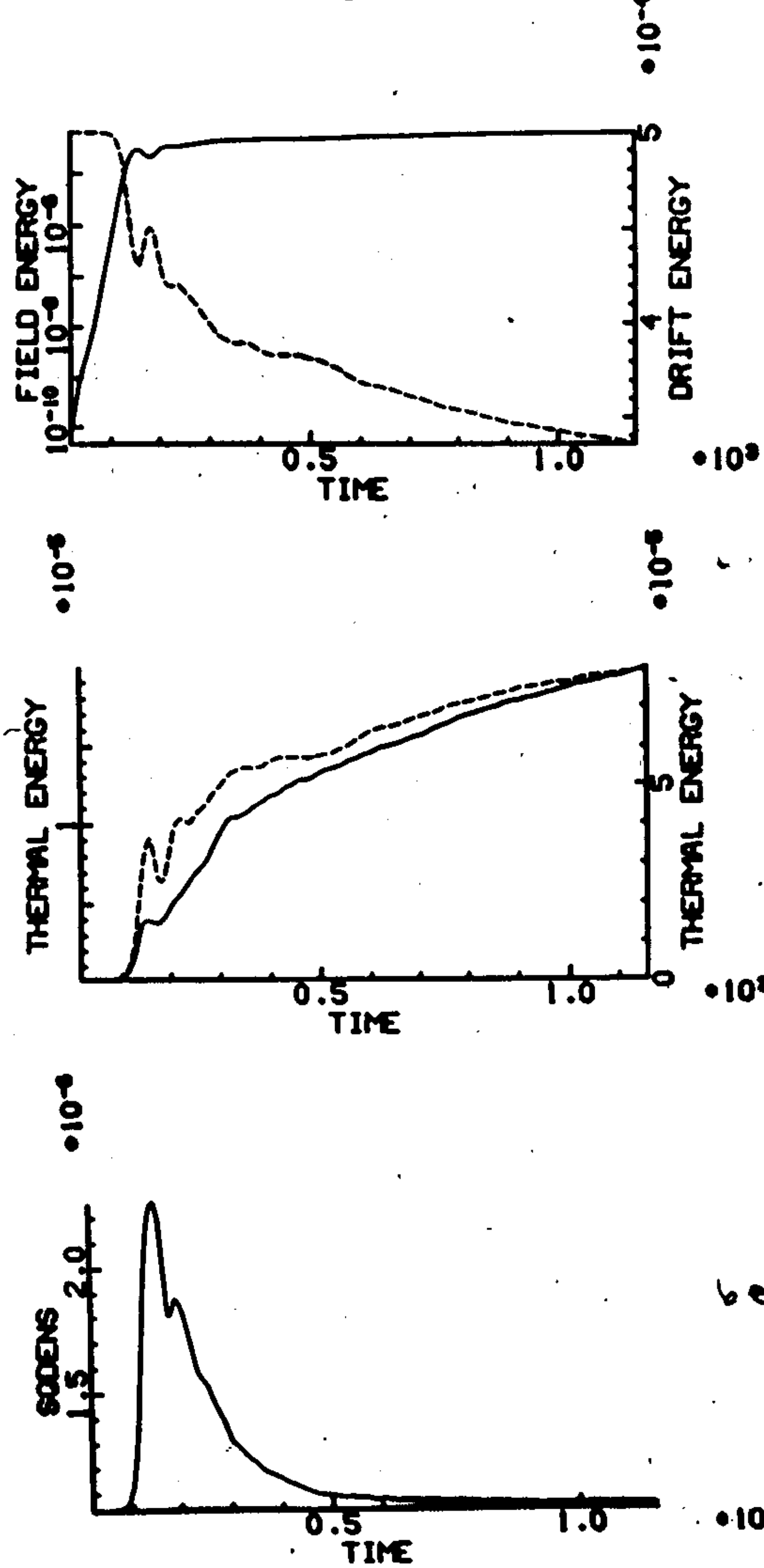
Fig. 1



$\hat{n}_b = 0.001 = \frac{n_b}{n_e}$
$\hat{T}_b = T_b/mu^2 = 3.10^{-4}$
$\hat{T}_e = T_e/mu^2 = 0.02$

Reactive Instability of an electron beam

Fig. 2

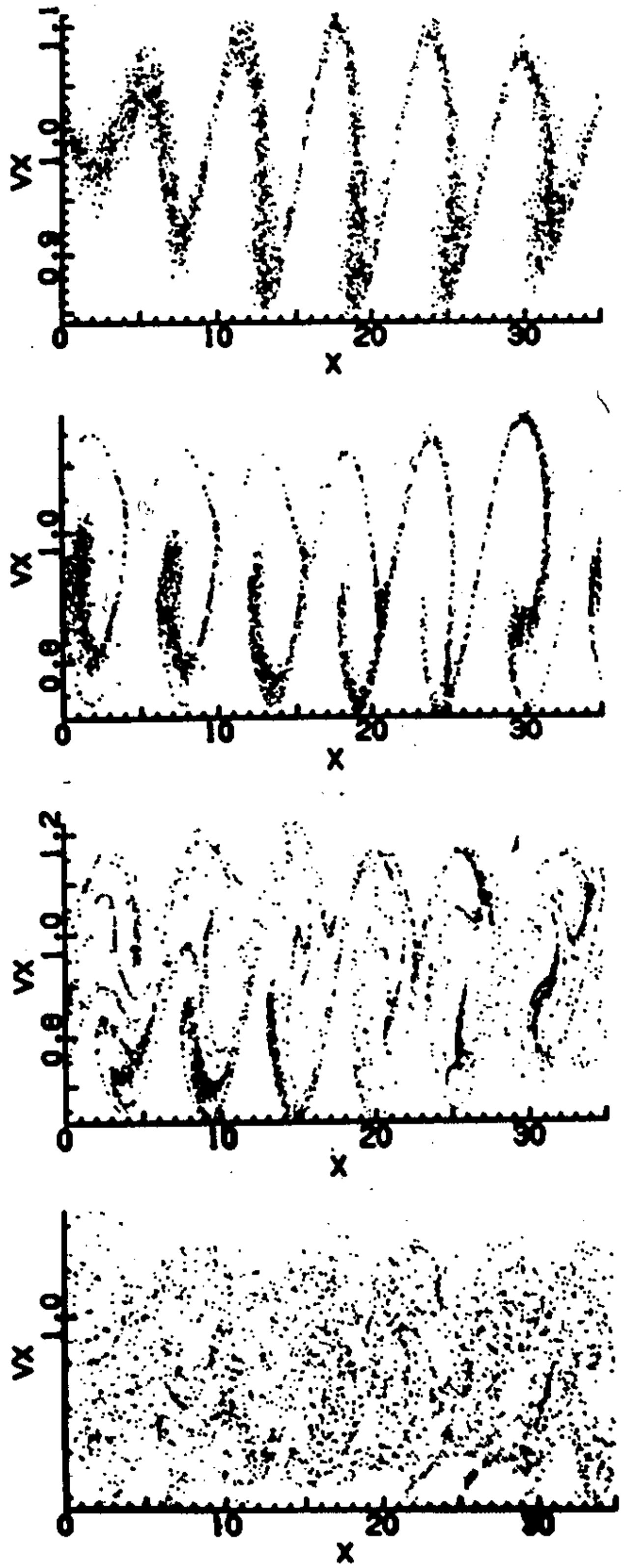


beam modulation
$\langle n_b(x)^2 \rangle_L$

C.T DUM
JGR 85, 8111 (1980)

$\hat{n}_b = \frac{n_b}{n} = 0.001$
$\hat{T}_b = T_b/mu^2 = 3.10^{-4}$
$\hat{T}_e = T_e/mu^2 = 0.02$
Hybrid

Fig. 3



$\omega_e t = 126.7$

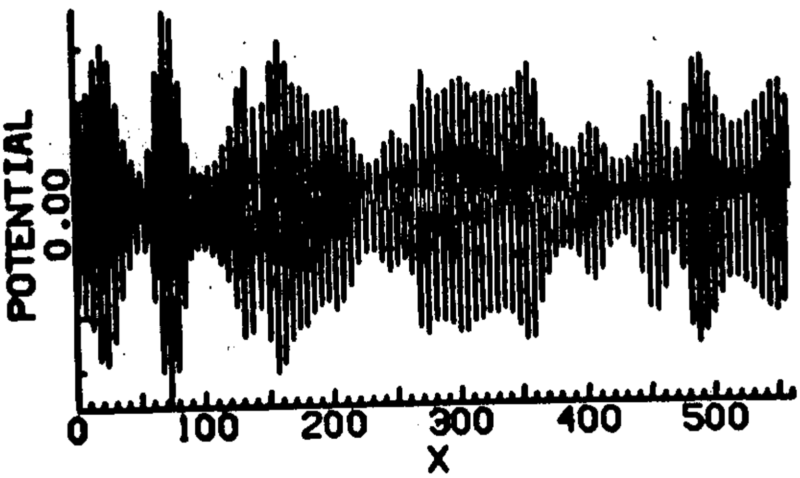
158.3

253.4

396

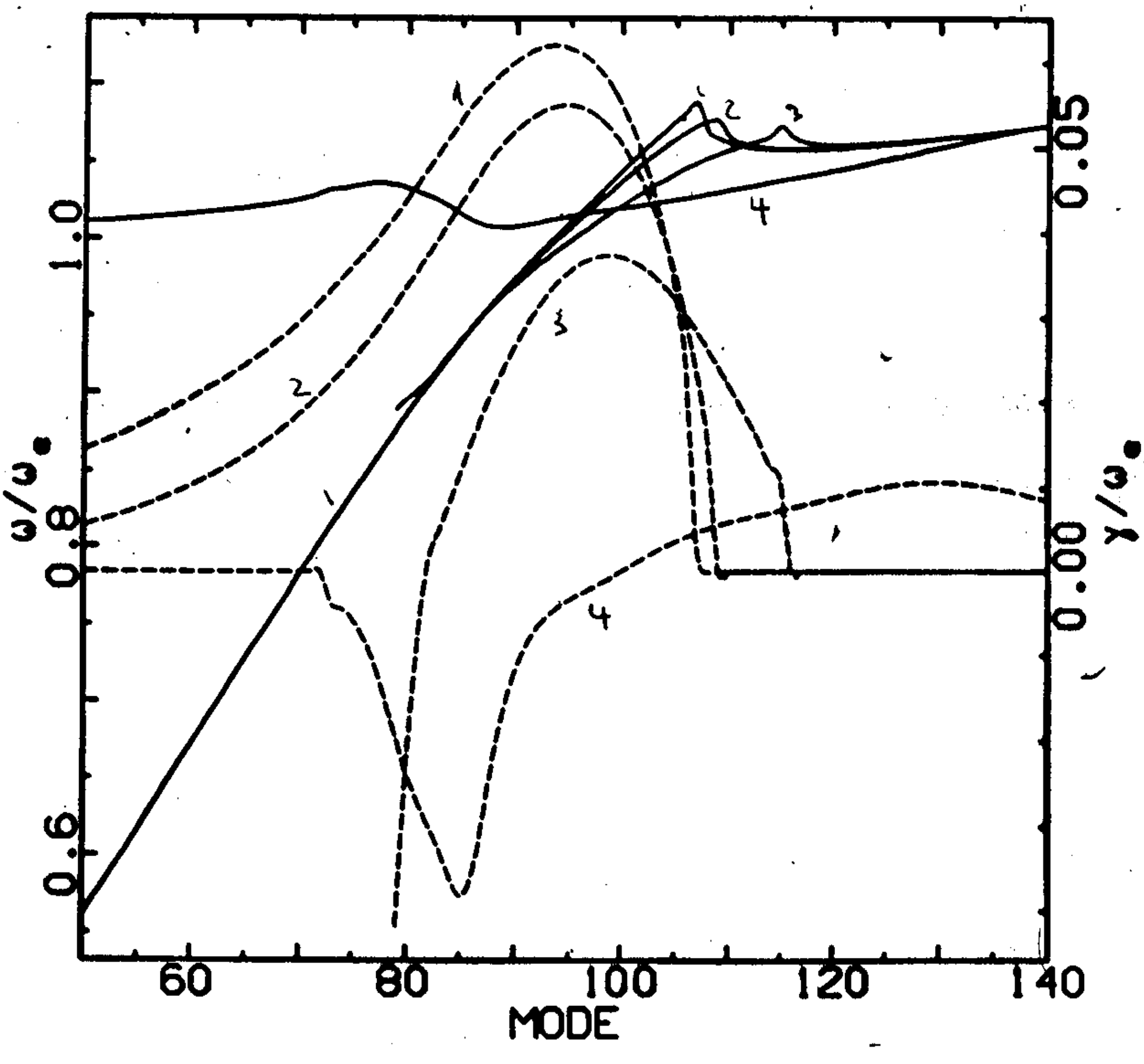
trapping & phase mixing at late times

Fig. 4



$\omega_e t = 158.4$

Fig. 6

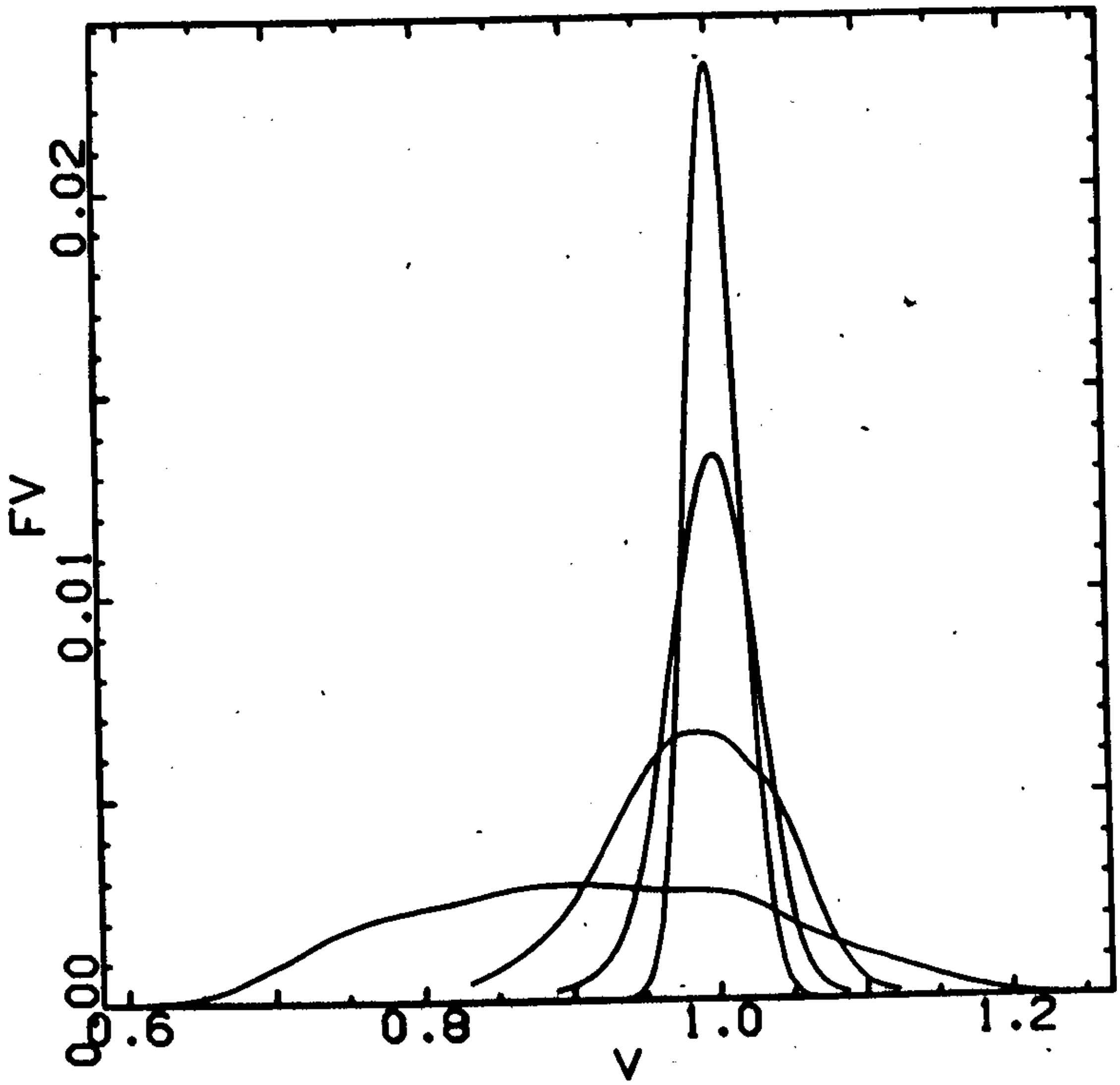


$\omega_e t = 15.8,\ 110.3,\ 126.3,\ 253.4$

$\frac{n_b}{n} = 0.001 \quad \frac{T_b}{nmu^2} = 3\ 10^{-4} \quad \frac{T_e}{nmu^2} = 0.02$

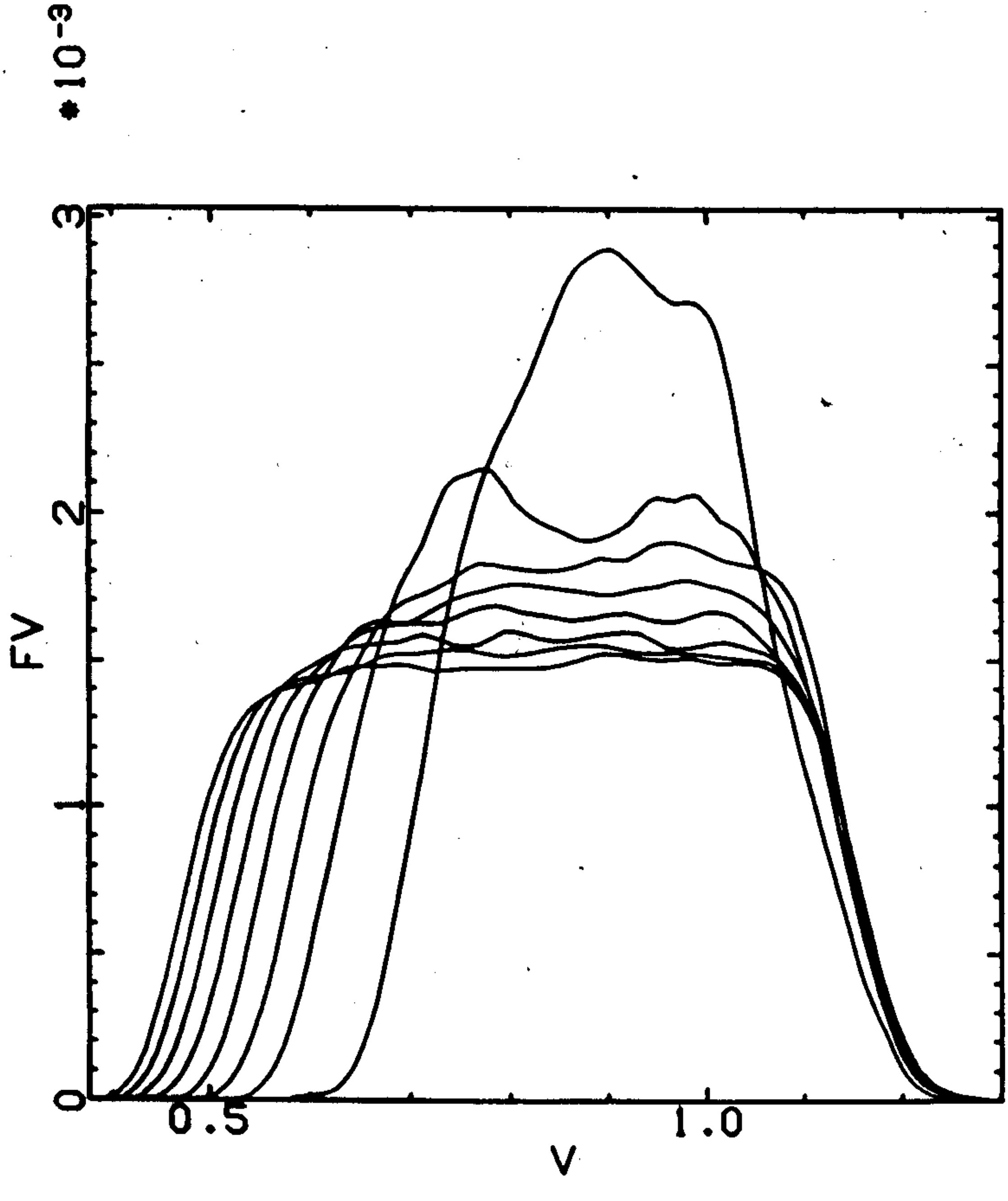
transition from reactive beam mode to kinetic plasma mode as beam is broadened. (cf. Fig 7)

Fig. 7



wet = 15.8, 110.9
126.7, 253.4

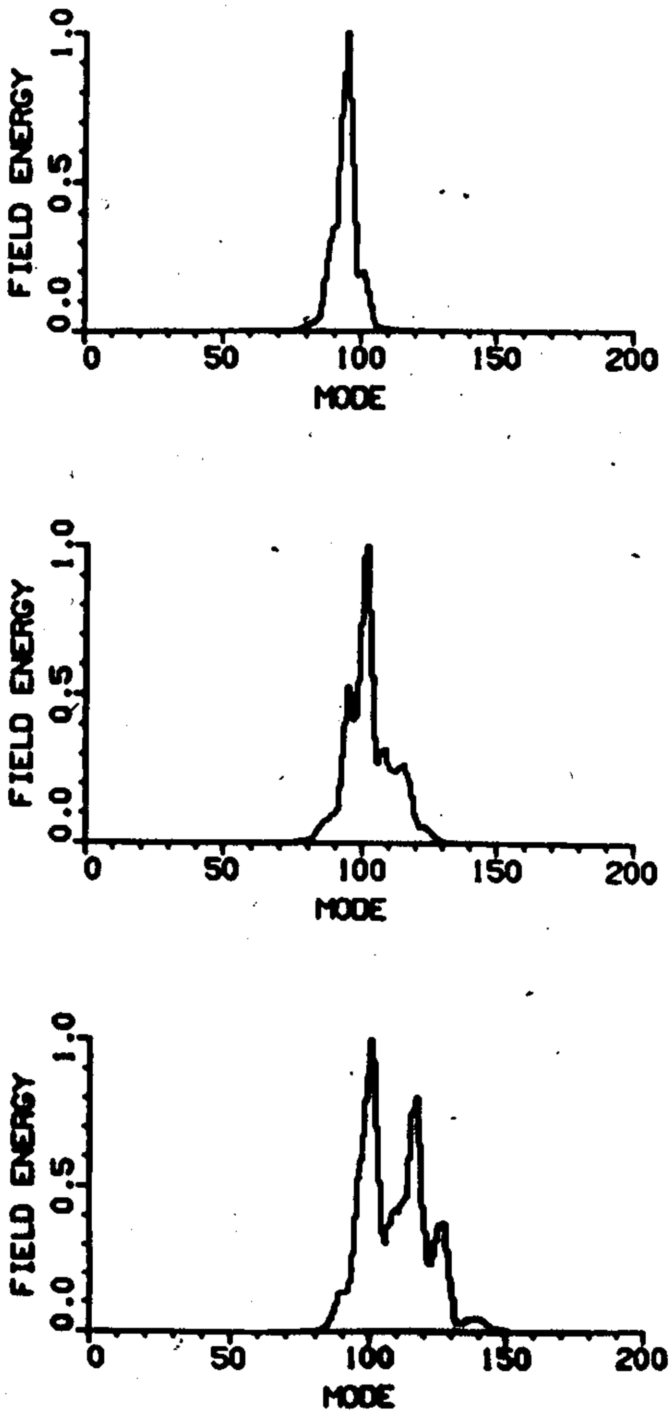
Fig. 8



late
kinetic
phase

ωt = 253.4, 380.1
506.9, 633.6
760.3
1014, 1140

Fig. 9

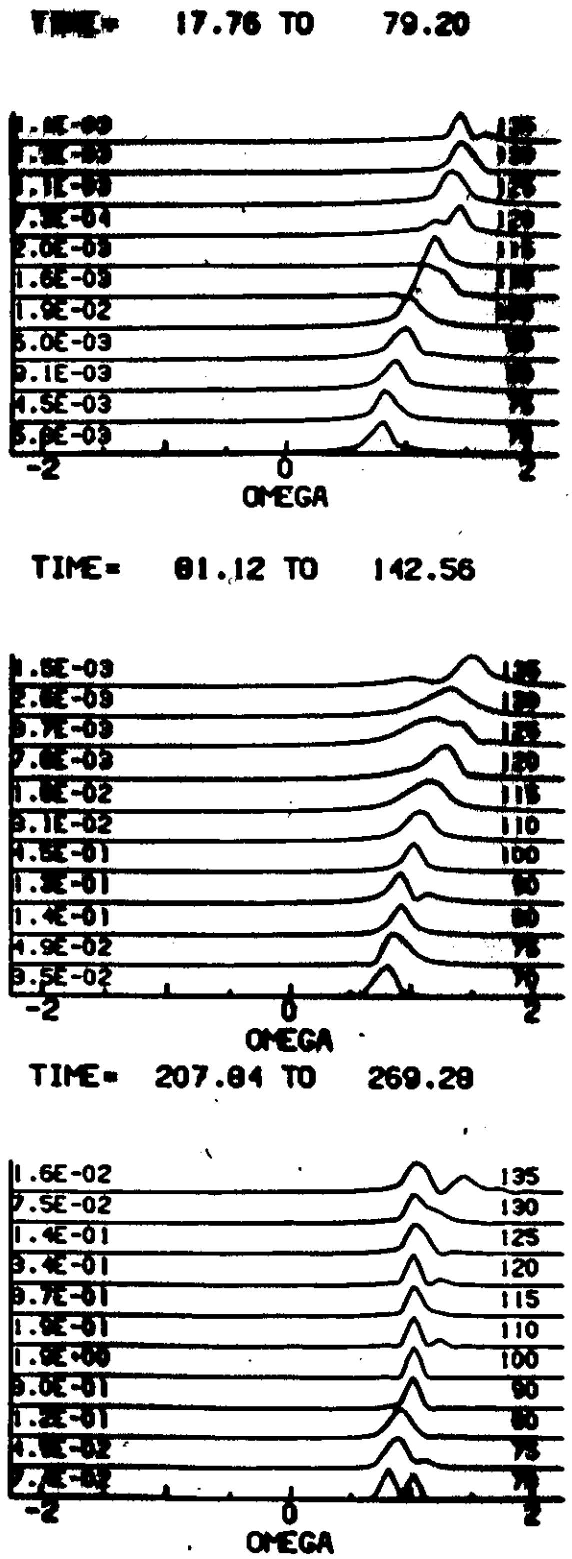


ωet= 158.3

253.4

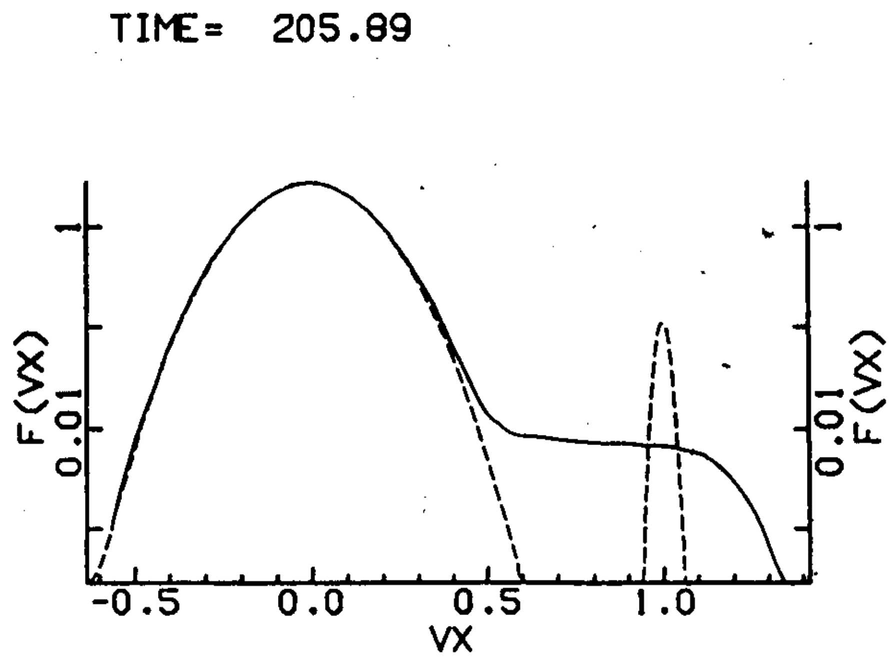
395.9

Fig. 10



transition from beammode $\omega k.u$ to plasmamode ω_{pe}

Fig. 12



late electron distribution

V Down shifted Oscillations

1. Observations

$v_c = \frac{d}{DIFF} V_{SW}$

$u/v_e = O(1)$ deep inside foreshock

Fuselier et al. 1985 $\omega < \omega_e$

2. Linear theory

not plasma eigenmode but
negative energy beam mode $\omega \lesssim k.u$
destabilized by bulk electron
Landau damping

$0 < \omega < \omega_{max}(\hat{T}_b, \hat{T}_e)$

3. Nonlinear Evolution: Particle Simul.

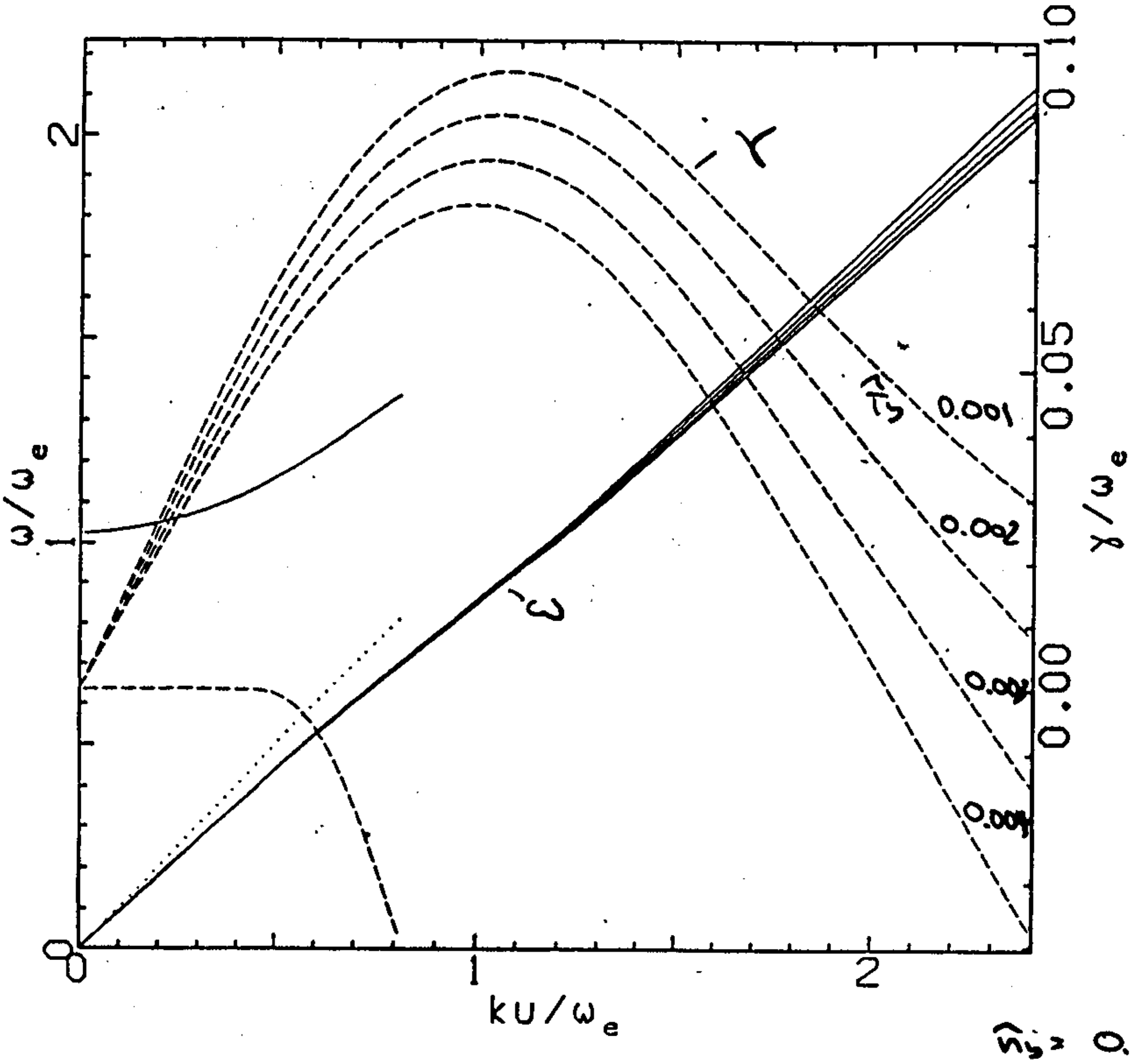
bump-in-bulk
Large γ
bulk diffusion
spectrum ω, γ persist for
distribution fn long time

Q.L. — · —

VI Overall Conclusions

Quasilinear Evolution
in space: injection $\parallel B$
convection by SW
across B

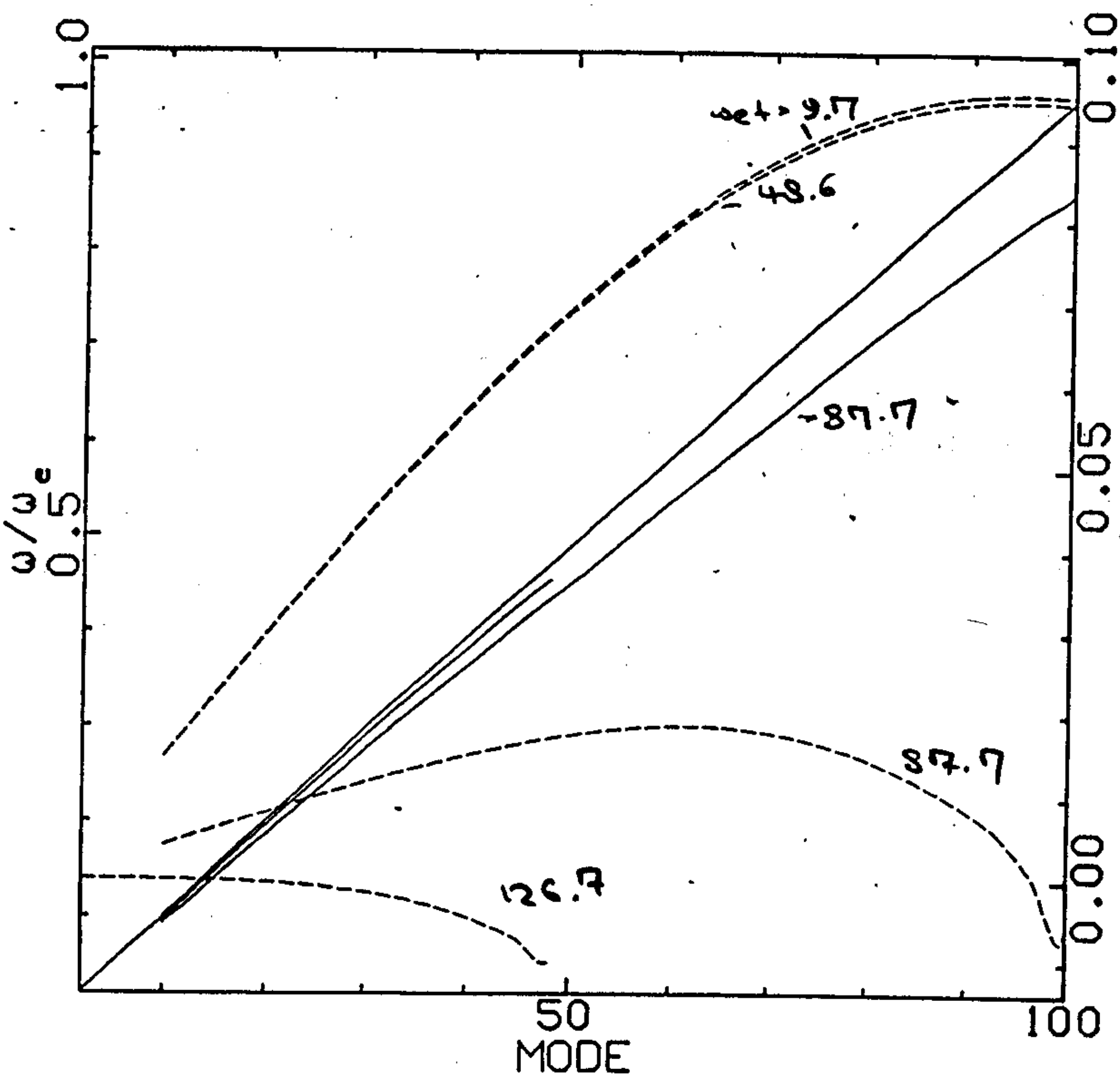
N.L effects (mode coupling)
not significant
for foreshock: cannot prevent
plateau formation



$\hat{n}_b = 0.05$
$\hat{T}_e = 0.25$

Figure 1

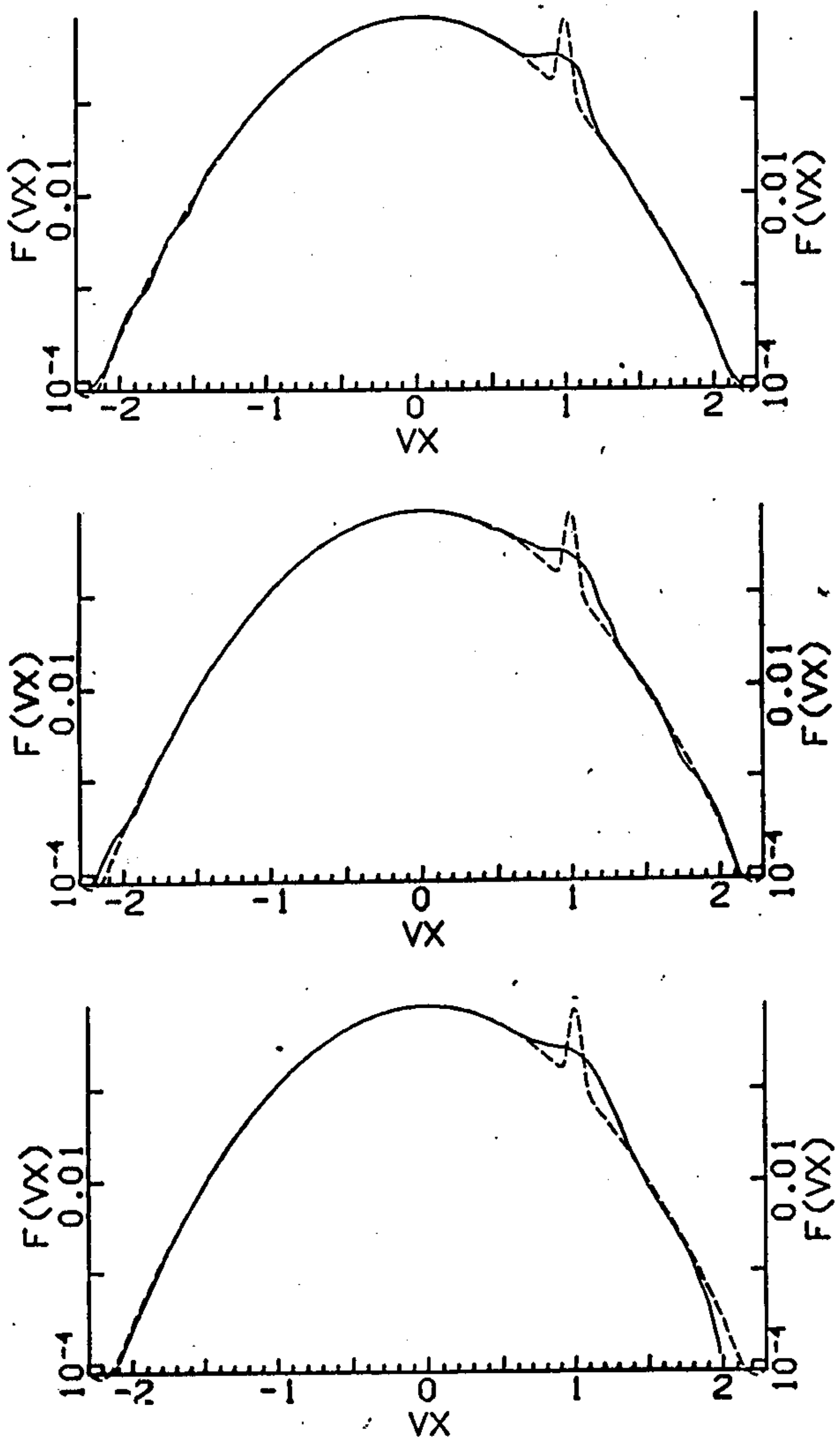
dispersion relation
for downshifted oscillations



Evolution of dispersion relation

Figure 2

corresponding to evolution
of distribution function (Fig 3)



ωet > 87.7

126.6

844.9

Figure 3

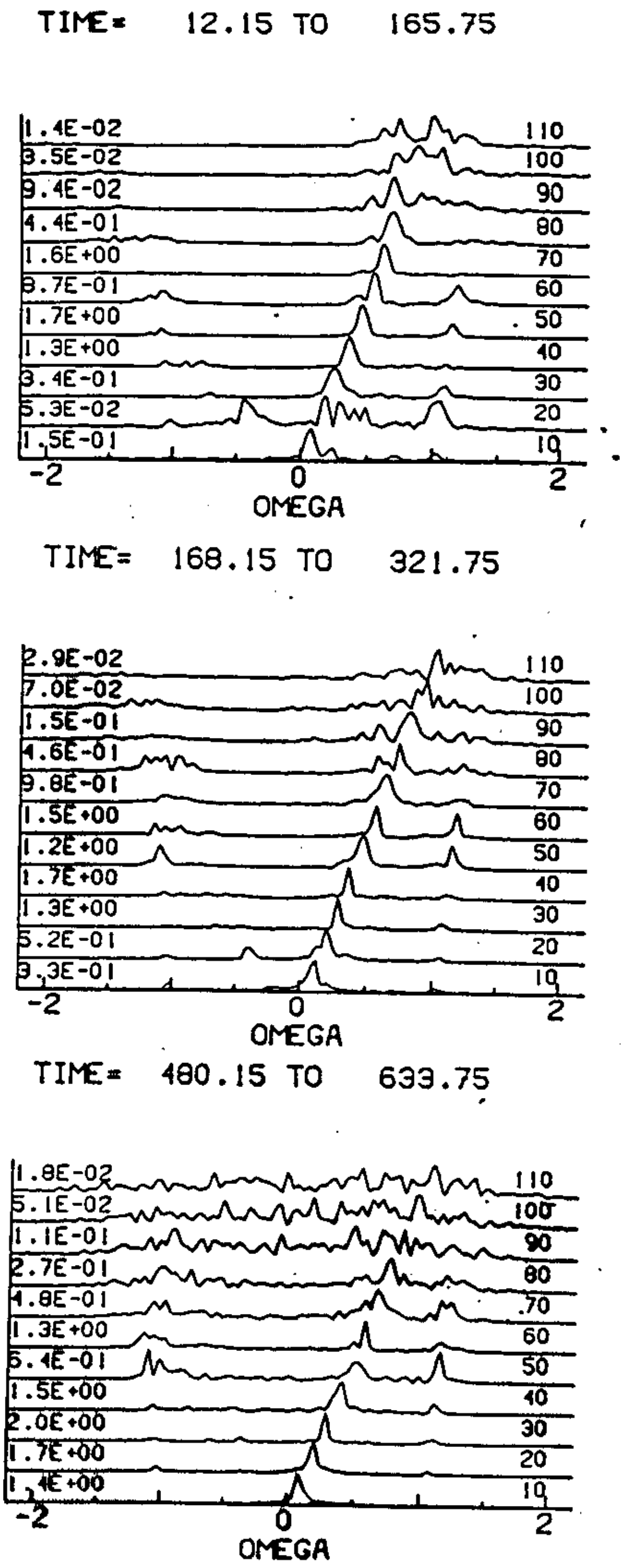
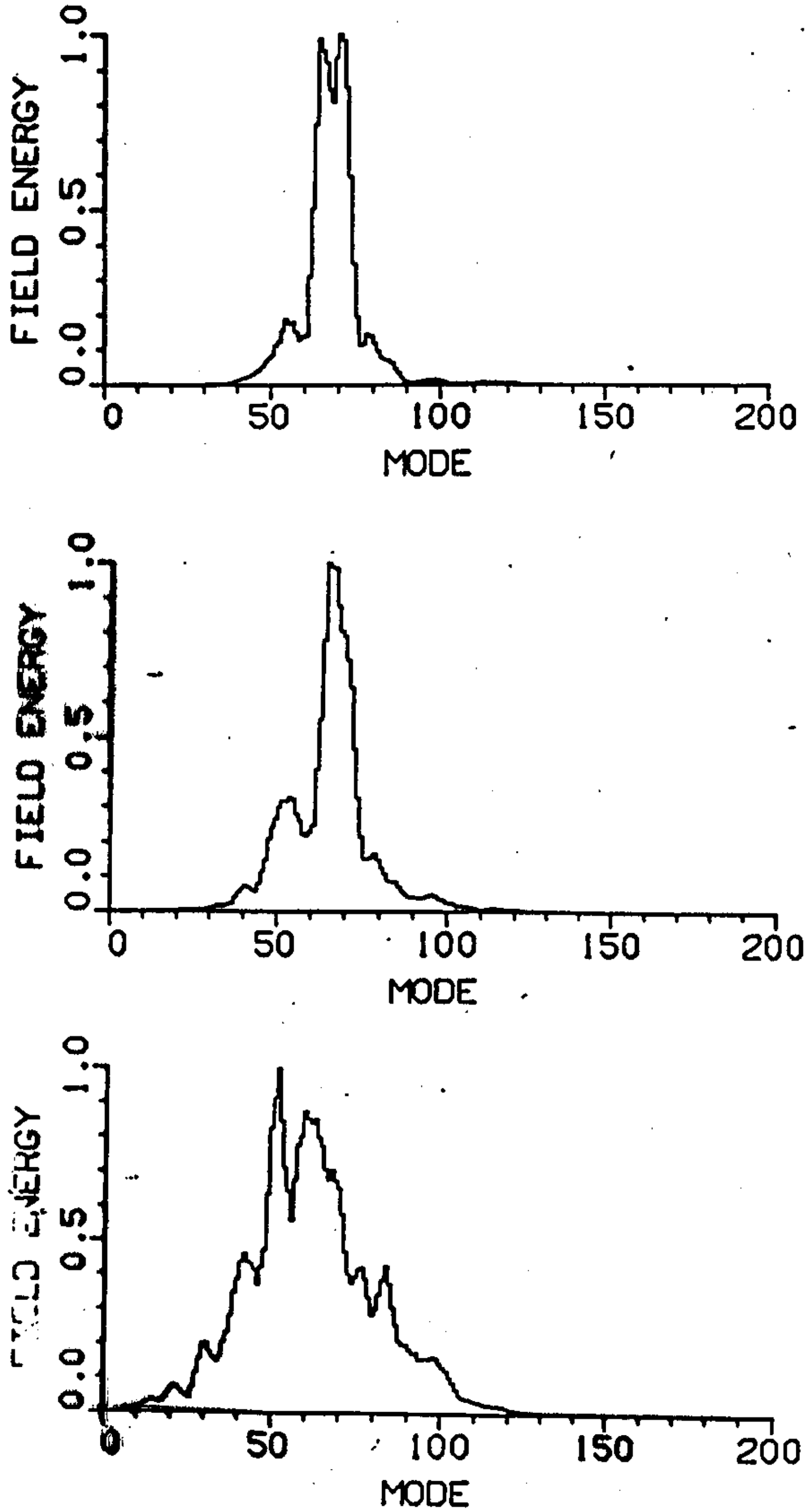


Figure 6

wave spectrum
ω vs mode number



$\omega_e t = 87.6$

126.9

594.6

Figure 7

Conclusions

1) Textbook approximations
have very limited range of applicability
kinetic instability
reactive instability
transition

2) Q. L. Theory

3) Nonlinear Mode coupling
(Scattering off ions) $\omega_k - \omega'_{k'} - (\underline{k} - \underline{k}')v = 0$
Secondary condensate $(\omega \lessgtr \omega_e)$
backward propagating waves

4) New regimes $\omega > \omega_e$
$\omega < \omega_e$ vel. persistent

5) Free energy source

6) Simulation
a) Linear dispersion relation
Design
Analysis : $f_j(\underline{v}, t)$ non Maxw
modification by strong driving!
$(\nabla b/n, \nabla b/u)$
$\rightarrow \omega(k, t)$ Topology changes possible
$\gamma(k, t)$

b) Number of modes (System size)
∞ spectra
c) Noise level
d) Hybrid simulations