INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SPRING COLLEGE ON PLASMA PHYSICS

(25 May - 19 June 1987)

PROGRESS ON ADVANCED ACCELERATOR CONCEPTS AT UCLA

Chan JOSHI

University of California
USA

PROGRESS ON ADVANCED ACCELERATOR CONCEPTS AT UCLA.

CHAN JOSHI

STATUS REPORT ON

1) The Plasma Beat Wave Accelerator

2) The Plasma Wake Field Accelerator

3) The Plasma Lens

4) Plasmas as Wigglers for Synchrotrons.

Work in collaboration with

J. Dawson, T. Katsouleas and W. Mori

F.F. Chen, C. Clayton

C. Darrow, D. Umstadter, J.J. Su, W. Mori, R. Williams.

Objectives

1 Explore the suitability of plasmas for accelerating particles at a very rapid rate.

2 Explore the suitability of plasmas for "wiggling" an electron beam and thereby obtain radiation.

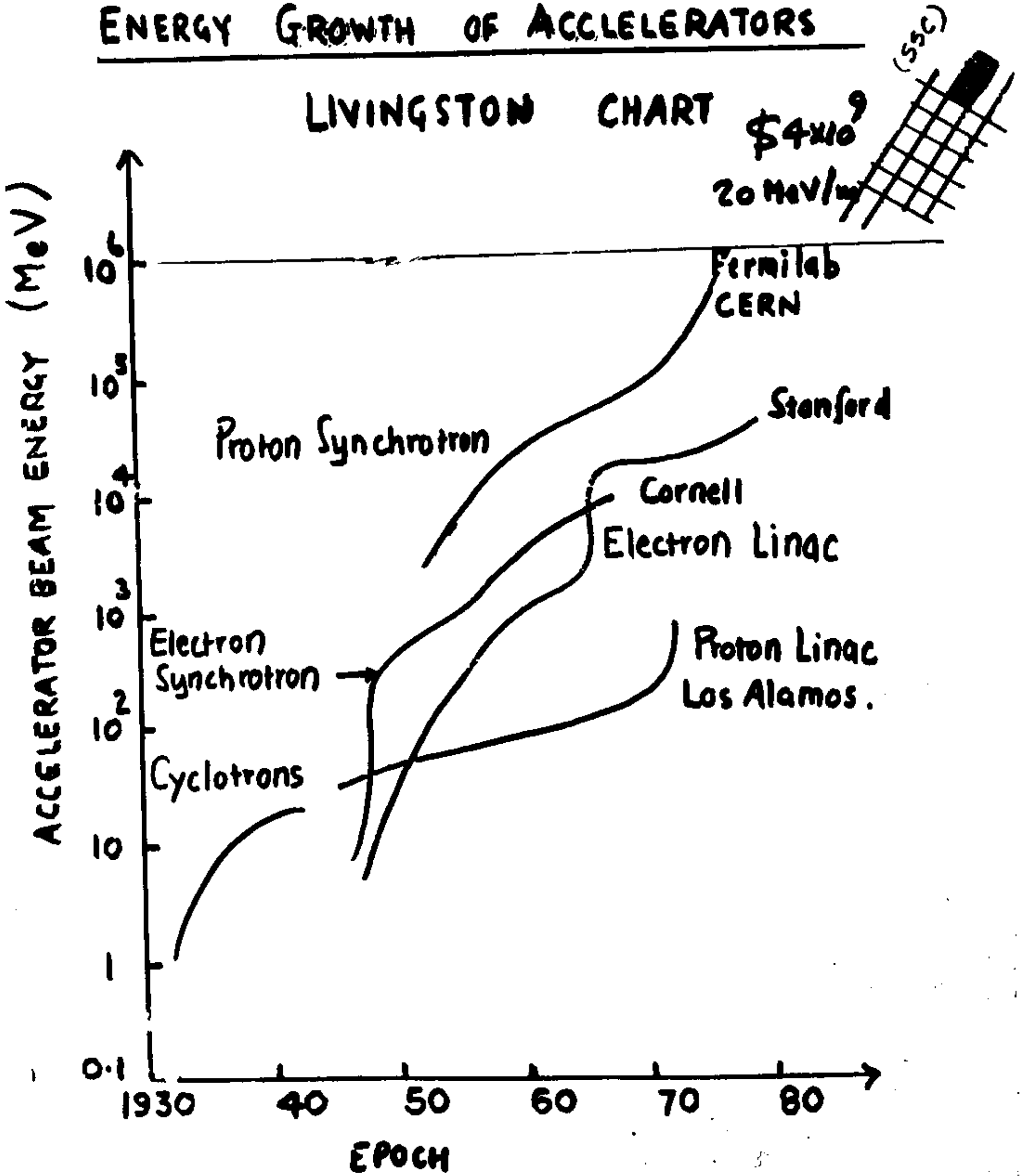
3 Explore the use of plasmas for focusing high energy beams

4 Develop laser, accelerator and plasma source technology to accomplish above

5 To train students and maintain UCLA's position at the forefront of this research.

ENERGY GROWTH OF ACCLELERATORS

LIVINGSTON CHART

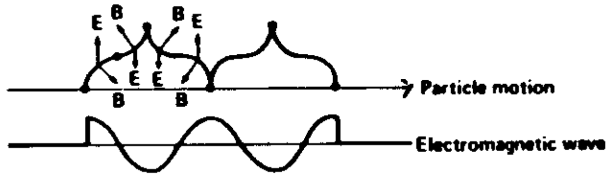


Why Use Lasers?

Electric Fields of 1 TeV/m

but

The field is transverse



thus

Particle displaced but sees no continuous acceleration

∴ Must find some way of coupling the transverse field to an accelerating mode having longitudinal E.

but

Laser propagates at c in vacuum

∴ Must propagate the laser in a gas or a plasma

or use a FEL

but

Interaction Limited by finite Rayleigh Length.

Can We Design a Conventional Linac to Operate at Optical Frequencies?

Why?

At microwave frequencies breakdown field scales as $\sqrt{f}$ (?)

~ 100 MeV/m at 2.8 GHz posible ?

Stored energy scales as $1/f^2$

~ large gain in going to 30 GHz

Unfortunately

Power sources not sufficiently developed

- Laser driven photocathodes
- Free electron lasers

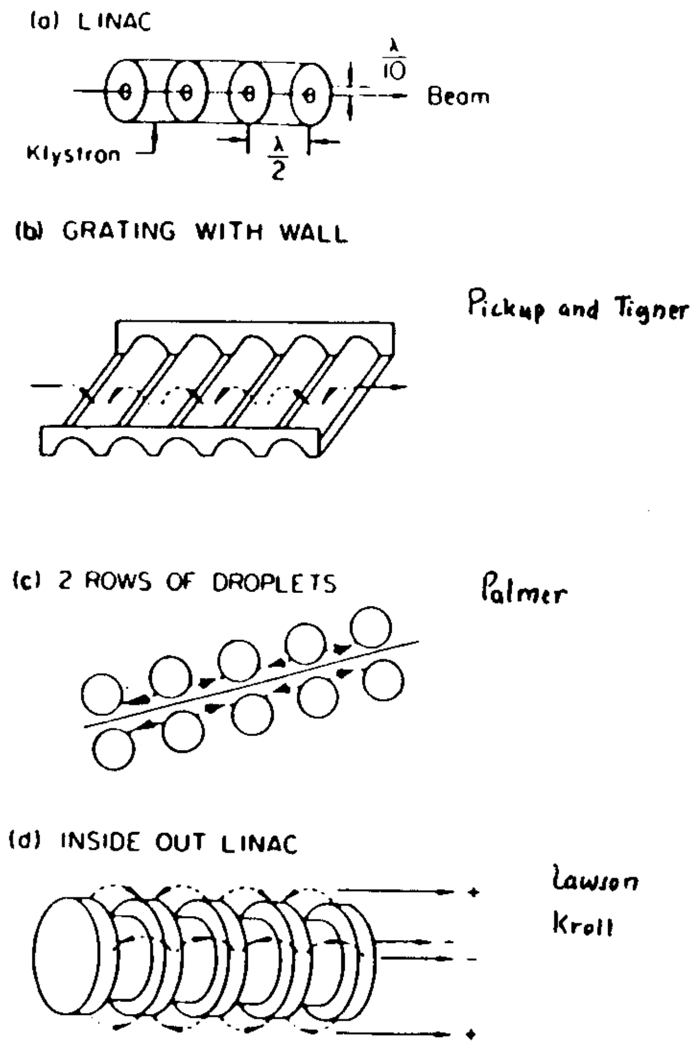
At optical Frequencies

Sources exist but frequency too high to use a closed cavity

CO_2 laser $f = 30$ THz , $\lambda = 10\ \mu m$

Structure size ~ 5 μm

LASER DRIVEN MICROSTRUCTURES



From: Summary of Working Group on Near field Accelerat. R. Palmer et. al Proceedings of Malibu Workshop.

RELATIVISTIC PLASMA WAVES

What are they ?

General Properties

Frequency $\omega_p = (4\pi n_0 e^2/m)^{1/2} \sim 6\times10^4\sqrt{n_0}\,(cm^{-3})$

Wavenumber $k_p = \omega_p/c$

Maximum Amplitude $= eE_z/m\omega_p c \approx 1$

Consider Plasma Densities of between $10^{16}-10^{18}$ electrons cm^{-3}.

Frequency 1 - 10 THz

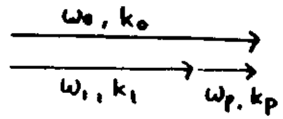
Wavelength 300 μm - 30 μm

Maximum Accelerating Fields : 10 - 100 GeV/m

APPLICATIONS: Basic Plasma Physics
Plasma Accelerators
Ultra-short wavelength Wigglers
Focusing of relativistic beams.

SPACE - CHARGE WAVES IN A PLASMA.

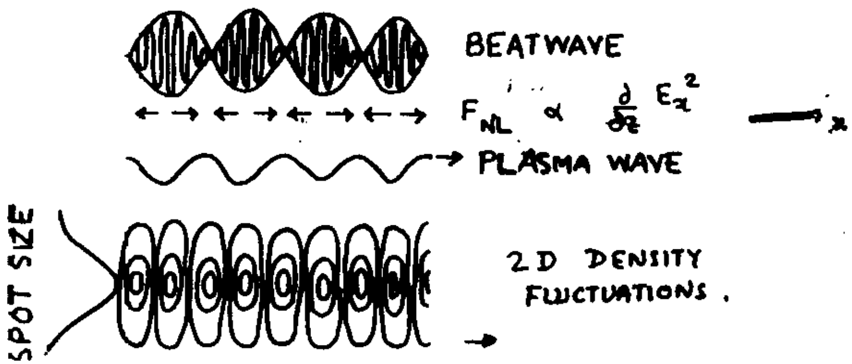
THE PLASMA BEAT WAVE ACCELERATOR



Inject two laser beams in an underdense plasma

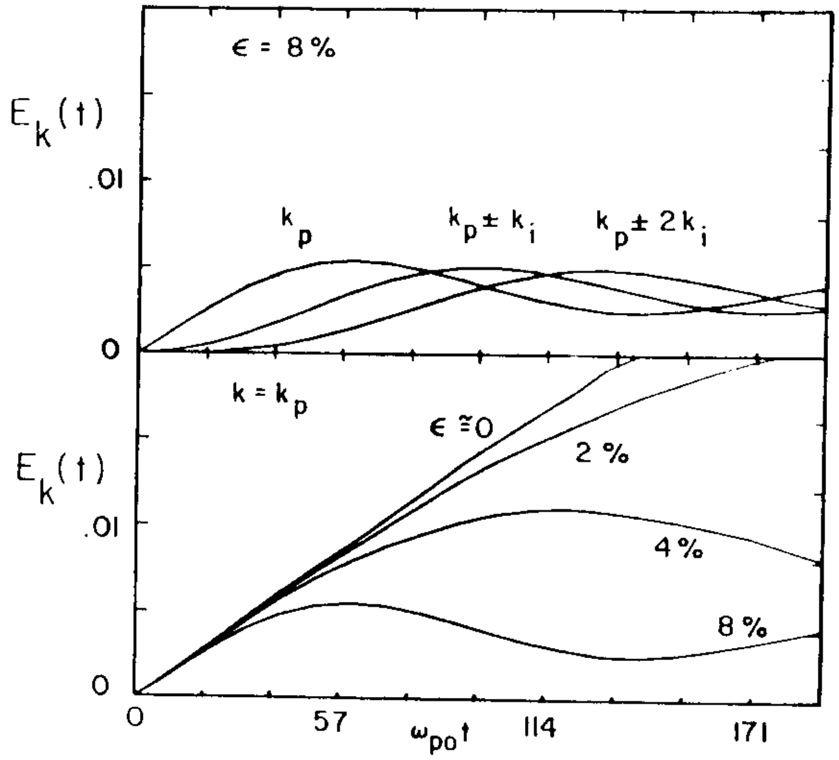
$\omega_0 - \omega_1 = \omega_p$

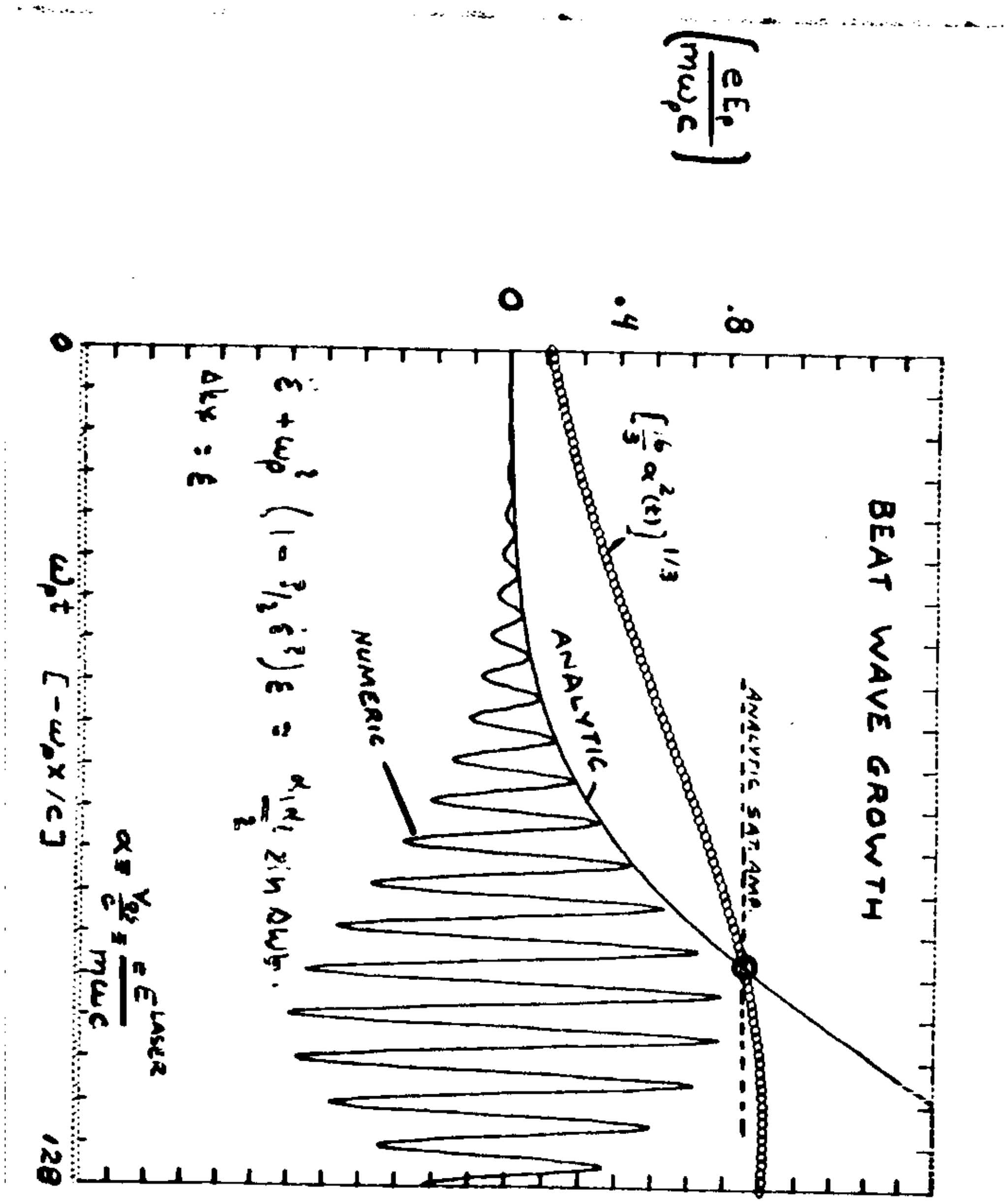
$k_0 - k_1 = k_p$



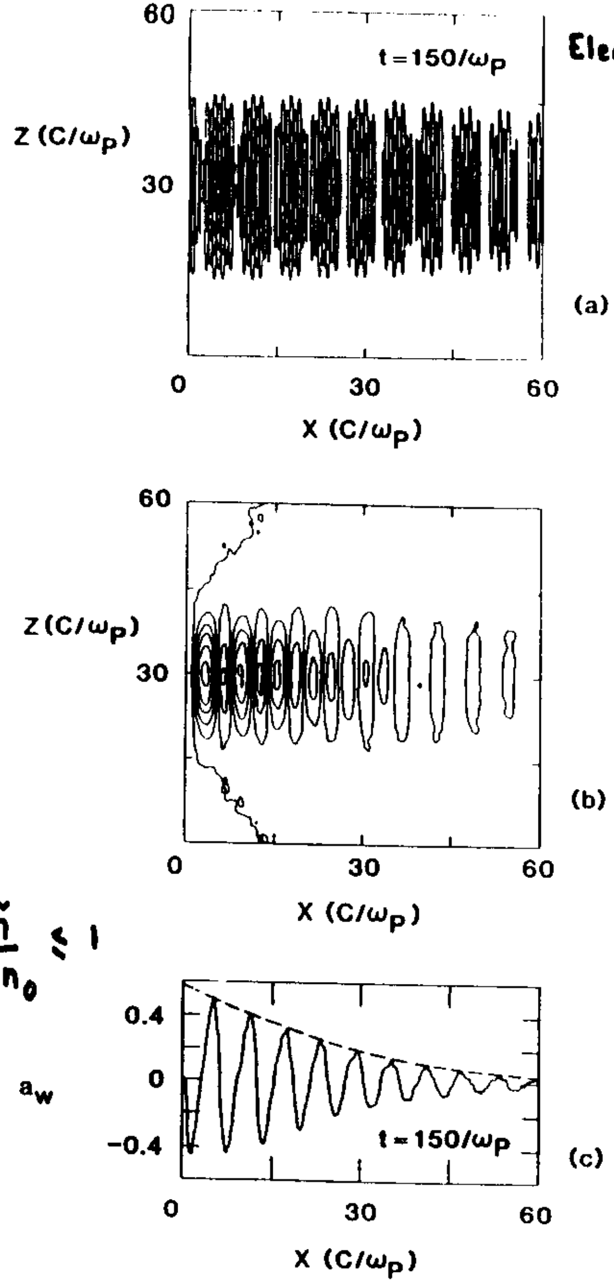
$$v_\phi = \frac{\omega_p}{k_p} \sim \frac{\Delta\omega}{\Delta k} \sim v_g = c\left(1-\omega_p^2/\omega_0^2\right)^{1/2}$$

UCLA, Rutherford, Osaka, NRS.


ε = 8 %
E_k(t)
.01
0
k_p
k_p ± k_i
k_p ± 2 k_i
k = k_p
ε ≅ 0
2 %
4 %
8 %
57
ω_po t
114
171


BEAT WAVE GROWTH
ANALYTIC
NUMERIC
ANALYTIC SAT. AMP.
0
.4
.8
128

Computer Simulations of Excitation of a Plasma (Purely - Electric) Wiggler.



$\approx \frac{eE_p}{m\omega_p c} \approx \frac{\tilde{n}}{n_0} \lesssim 1$

$\frac{v_0}{c}$ or a_w

Figure 4 Laser beat excitation of plasma wiggler.

PLASMA WAKE FIELD ACCELERATOR

Power density in electron bunches can exceed that obtained using lasers.

	SLC	Modest Linac
N	5×10^{10}	5×10^{10}
r	1·5 μm	50 μm
V	50 GeV	10 MeV
Δz	0·6 mm	0·6 mm
I =	2×10^{21} W/cm^2	5×10^{14} W/cm^2
n_b =	7×10^{18} cm^{-3}	1×10^{16} cm^{-3}

What happens if we shoot such a bunch into a plasma?

Plasma acts as a single-mode, slow-wave structure.

Wake Fields Excited by Shaped Bunches

UCLA : SLAC

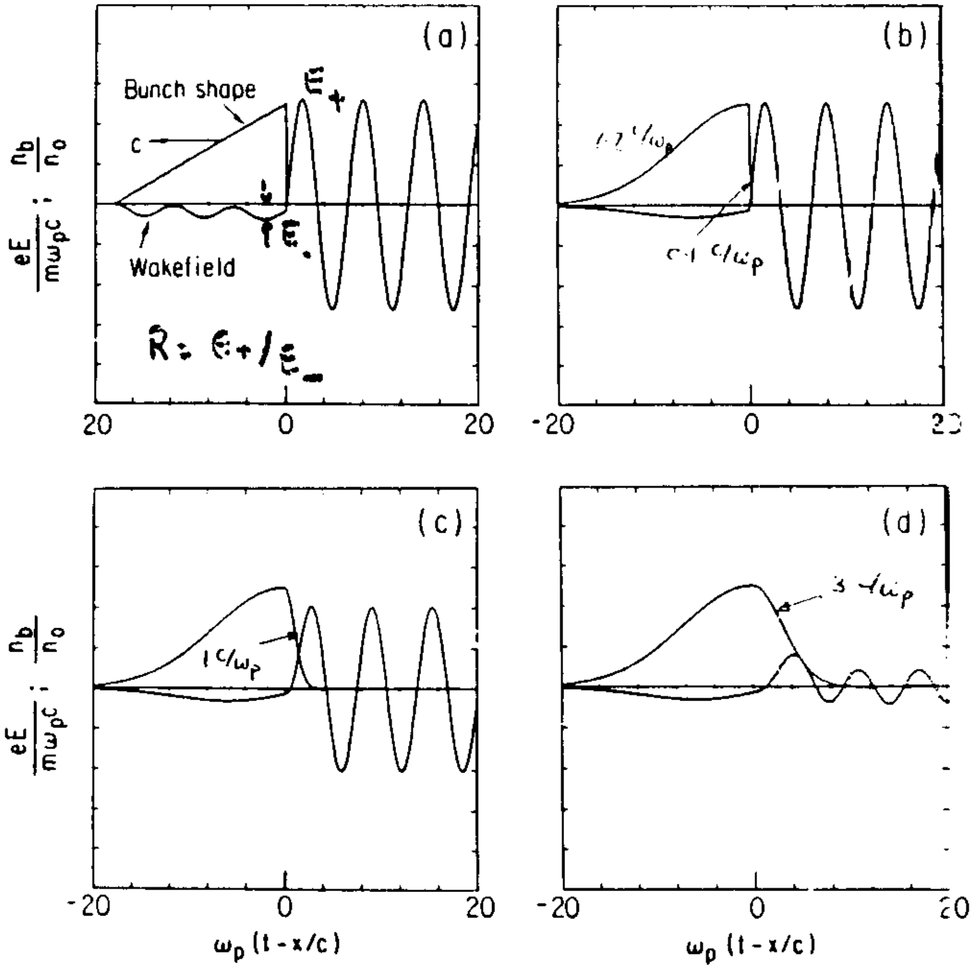
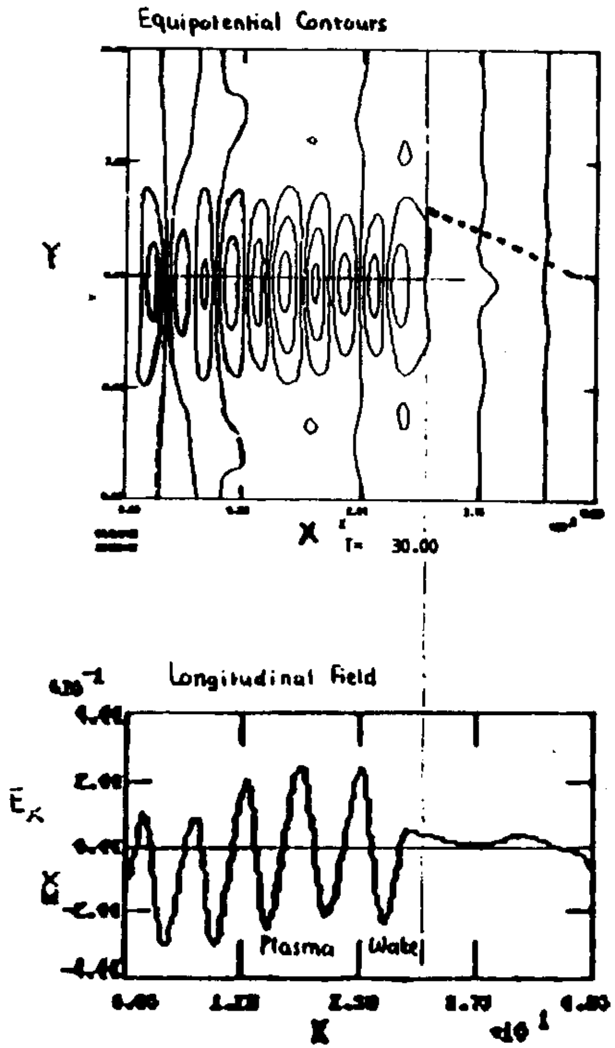


Figure 2 Numerical solutions of 1-D wakefields produced by various bunch shapes: (a) Triangular bunch; (b) gaussian rise $\sigma_r = 7.2\ c/\omega_p$, gaussian fall $\sigma_f = .1\ c/\omega_p$; (c) $\sigma_r = 7.2\ c/\omega_p$, $\sigma_f = 1\ c/\omega_p$; (d) $\sigma_f = 3\ c/\omega_p$.

Recent 2D Particle Simulations (UCLA)



EXPERIMENTAL PARAMETERS

HYDROGEN PLASMA PARAMETERS

$n_e \approx 10^{17}\ cm^{-3}$ ← $\omega_0 - \omega_1 = \omega_p$

$T_e \approx 30\text{–}50\ eV$

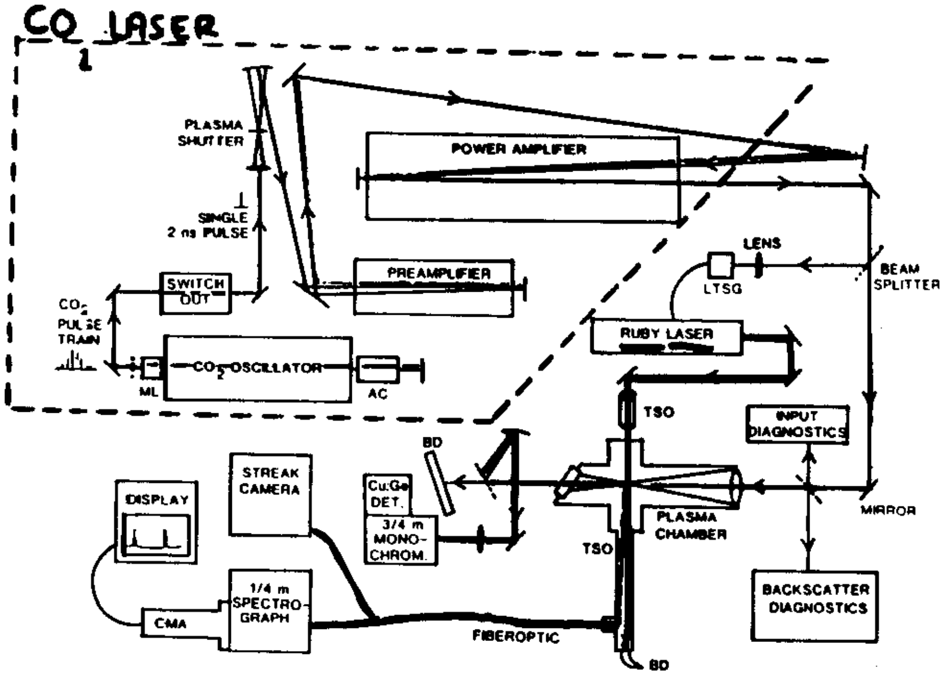
$L > 10\ mm$

$L_n \sim 2\ mm(?)$

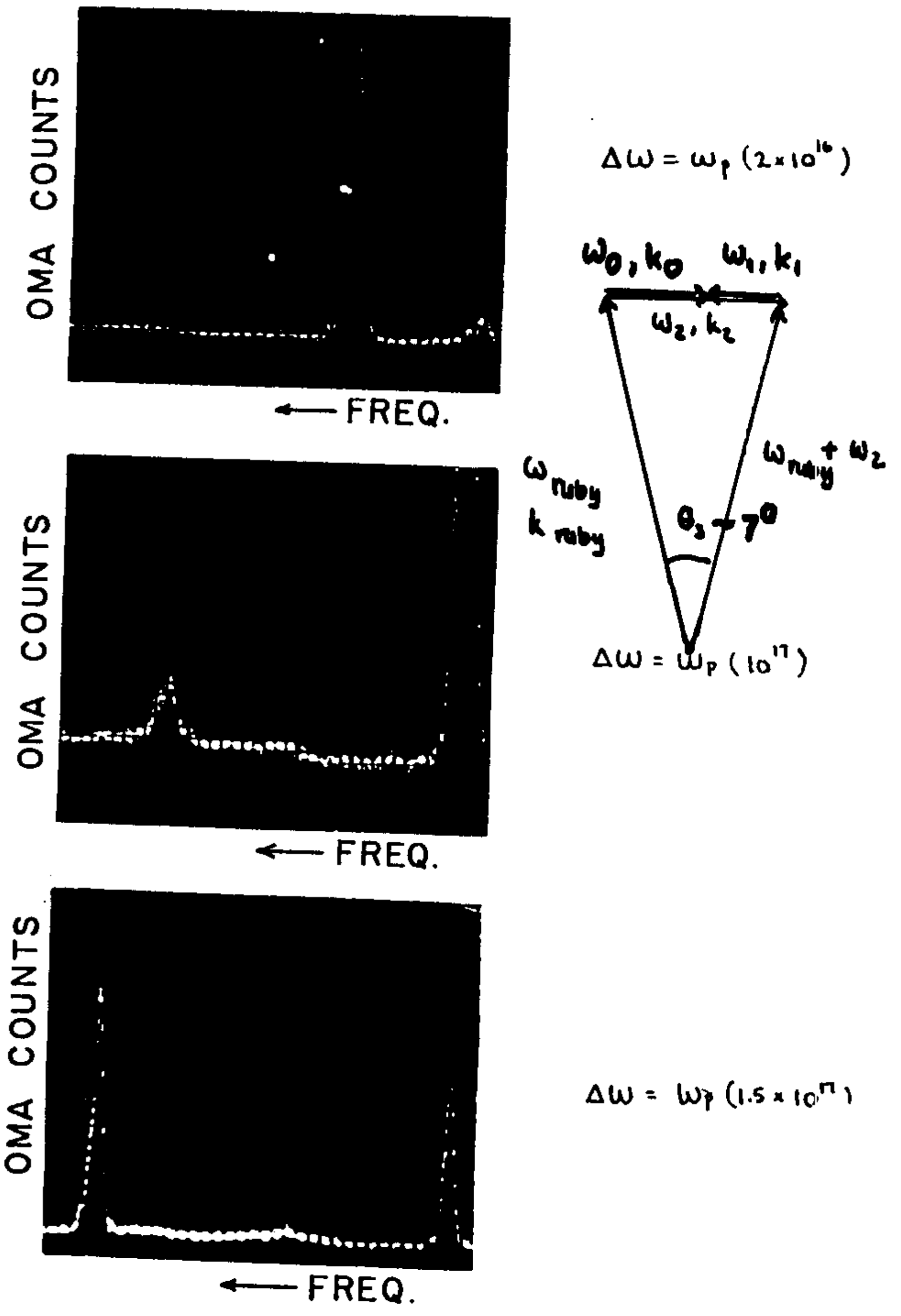
CO_2 LASER PARAMETERS

$E_o \approx 20\ J$	$\tau \approx 2\ nsec$
$P_o \approx 8\ GW$	$\lambda_o \approx 10\ um$, 10.6 + 9.6 μm
$I_o \approx 10^{13}\ W/cm^2$	$2w_o \approx 300\ um$
$v_{os}/c \approx 3\%$	$2z_o \approx 8\ mm$

EXPERIMENTAL SET-UP.



SLOW WAVE THOMSON SCATTER SPECTRA



DETECTION OF BEAT EXCITED PLASMA WAVES: UCLA

1) Use two independent techniques

- CO_2 Thomson Scattering - collinear
- Ruby Thomson Scattering - transverse

2) Mode-coupling indirectly confirms the existance of the beat driven plasma wave.

CO_2 Laser, 10.6 μm and 9.6 μm

Peak Intensity ~ 10^{13} W/cm^2

Pulse Length ~ 1.5 ns (FWHM)

Plasma density ~ 10^{17} cm^{-3} (Hydrogen)

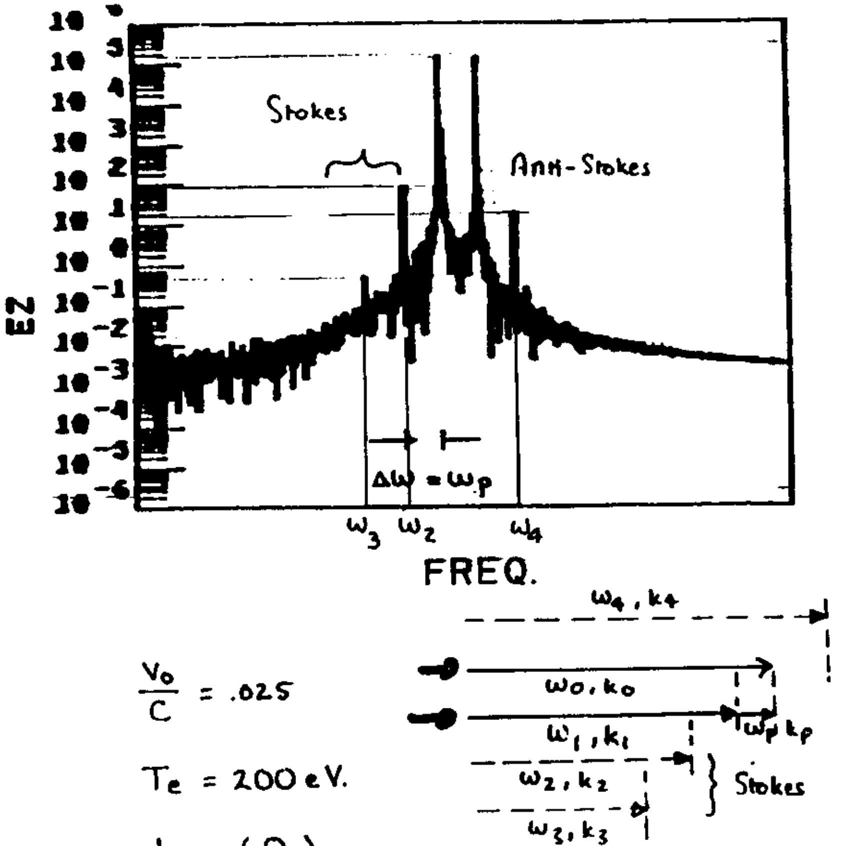
Plasma temperature ~ 20 eV.

EM SPECTRUM FROM SIMULATION

UCLA - Los Alamos

1 D MOBILE ION SIMULATIONS.

Peak $\frac{\tilde{n}}{n_0}$ = 4-5 %.



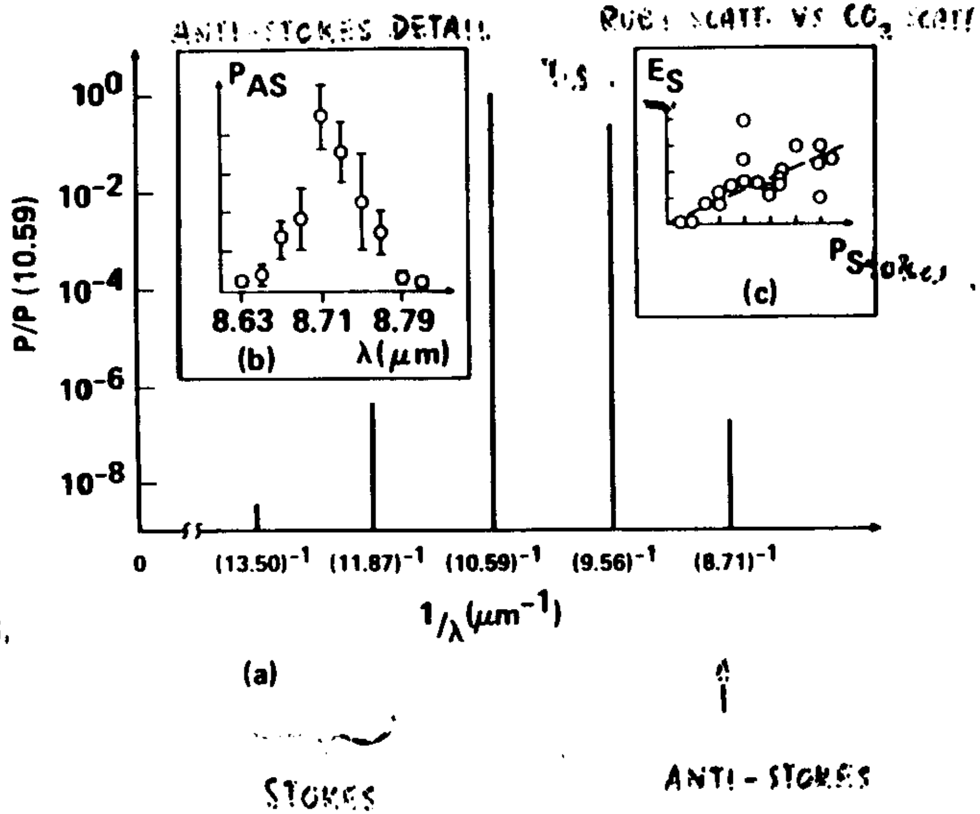
$\frac{V_0}{C}$ = .025

T_e = 200 eV.

$L = 60\,\lambda_p$

EXPERIMENTALLY MEASURED STOKE'S AND ANTI-STOKES SPECTRA

UCLA Expt.



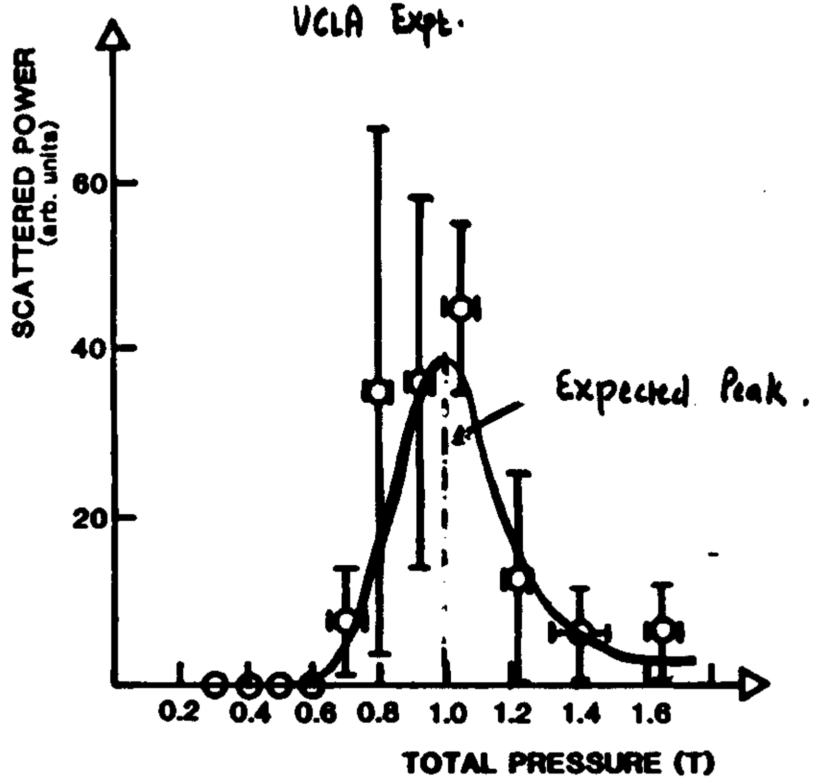
- Only observed with two frequencies
- Strongly peaked at resonant density

∴ NOT DUE TO RAMAN FORWARD SCATTERING.

C. Clayton et. al. Phys. Rev. Lett. 54, 2343 (1985)

OBSERVATION OF A DENSITY RESONANCE

UCLA Expt.

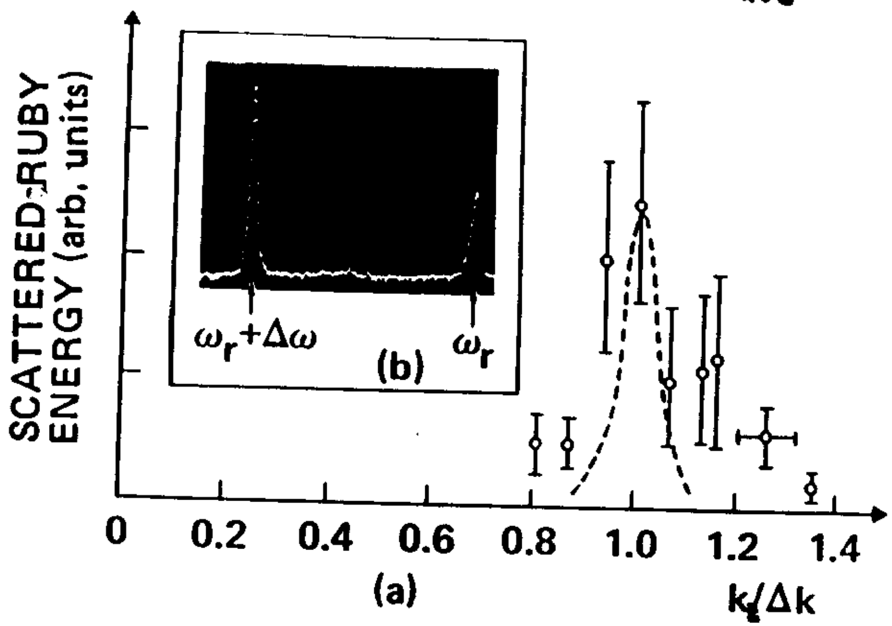


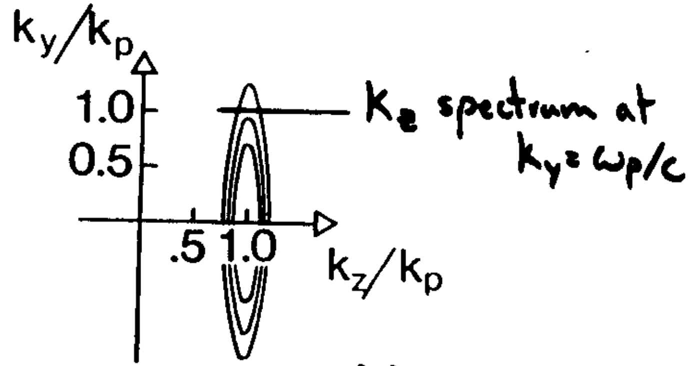
Remember Resonance Condition

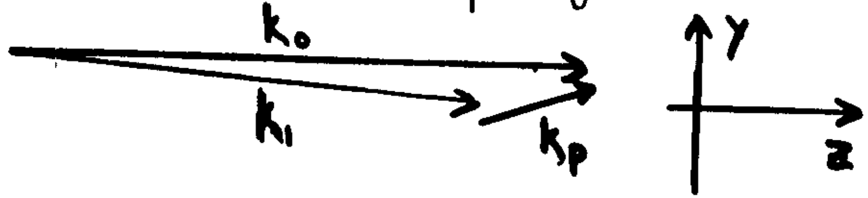
$$\omega_0 - \omega_1 = \omega_p$$

and $\Delta\omega = \omega_p$ at 1 Torr measured using Raman scattering.

ω and k_z Spectrum of Plasma Wave



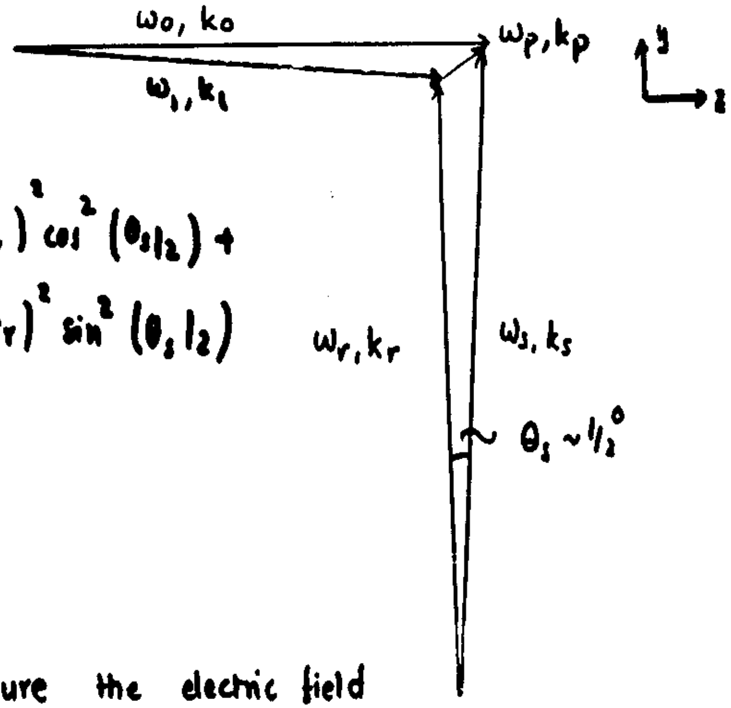




ω, k matching requires ruby scatter from wave with $k_z = k_y$

F. Martin et al : P.R.L

THOMSON SCATTER FROM WAVES WITH $v_\phi \sim c$



$$k_p^2 = (k_s - k_r)^2 \cos^2(\theta_s/2) + (k_s + k_r)^2 \sin^2(\theta_s/2)$$

We measure the electric field

of component of the wave (with $k_y = k_z$)

cf: F. Martin et. al
Phys. Rev. Lett.

PLASMA WAVE AMPLITUDE.

$$\frac{\text{Scattered Power}}{\text{Incident Power}} = \frac{L_{epw}}{L_o} \frac{\tau_{epw}}{\tau_o} \left(\frac{\pi}{2} \frac{\tilde{n}}{n_o} \frac{n_o}{n_c} \frac{d}{\lambda_o} \right)^2$$

We measure :

$$P_s = 10^{-9} - 10^{-10} P_{in}$$

$$L_{epw} = 0.2\, L_o$$

$$\tau_{epw} = 0.05\, \tau_o$$

$$n_o = 0.01\, n_c$$

$$d = 170\, \lambda_o$$

This gives $\tilde{n}/n_o = 1 - 3\%$ for $k_y = k_z$

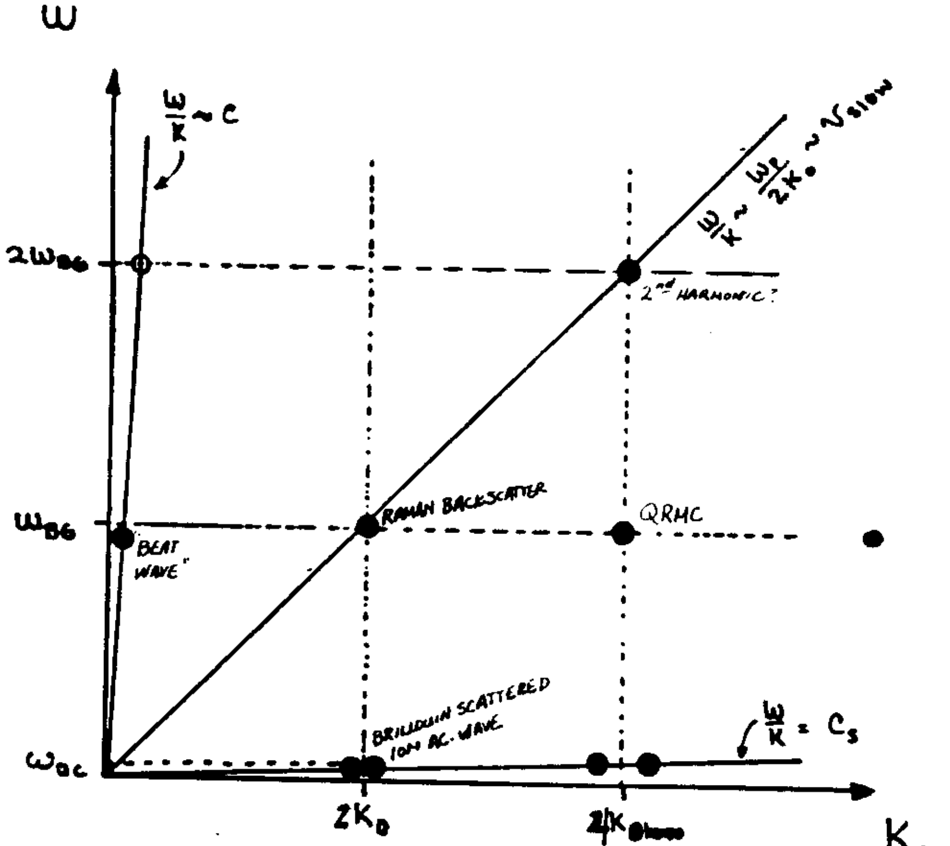
Thus $\tilde{n}/n_o$ for the beat wave is likely to be between

3 ~ 9% (from Geometric considerations)

$E_L \Rightarrow$ <u>600 MeV/m → 2.1 GeV/m.</u>

ELECTROSTATIC "ZOO"

24

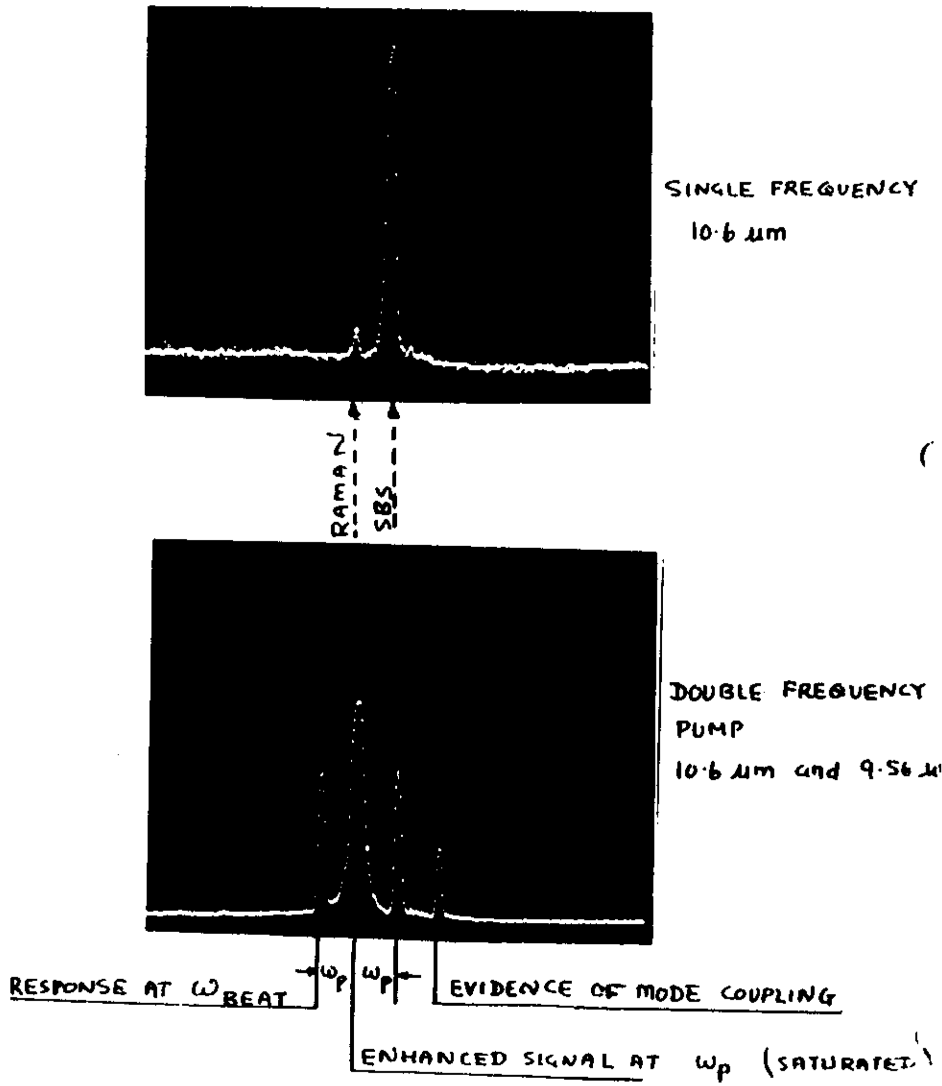


● OBSERVED

O. ANTICIPATED

Search For $\omega_{beat} = 2\omega_p$ Coupling. UCLA Expt (198

Thomson Scatter Frequency Spectra at $\Delta k \approx 2k_0$



MOTIVATION : Phase II Expts.

Demonstrate the suitability of relativistic plasma waves for electron acceleration.

- ✓ – excitation of large amplitude epws
- – injection of relativistic electrons
- – wave-particle interactions

CO_2 Laser is ideal for Proof-of-Principle Expt.

Wavelengths	Density (cm^{-3})	γ_{ph}	Accel. Length	Energy Gain
9.6 + 10.6 μm	1.1×10^{17}	10	3.3 mm	10 MeV
9.6 + 10.3 μm	6×10^{16}	13	15 mm	22 MeV

for 10% wave.

CO_2 Laser is ideal for POPE on PBWA.

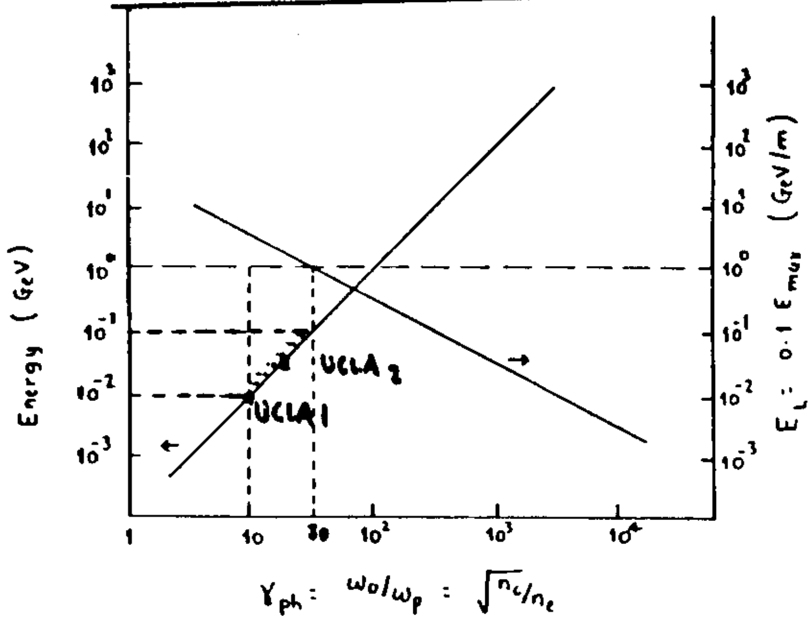
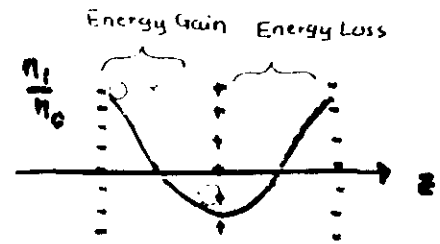


Fig. 2. Parameter regime for the plasma beat wave accelerator using a CO_2 laser.

$E_L = 0.1\, mc\omega_p/e$, Energy $= 0.1\, \gamma_{ph}^2$ MeV

$10 < \gamma_{ph} < 30$ we obtain

$10 < E\,(MeV) < 100$



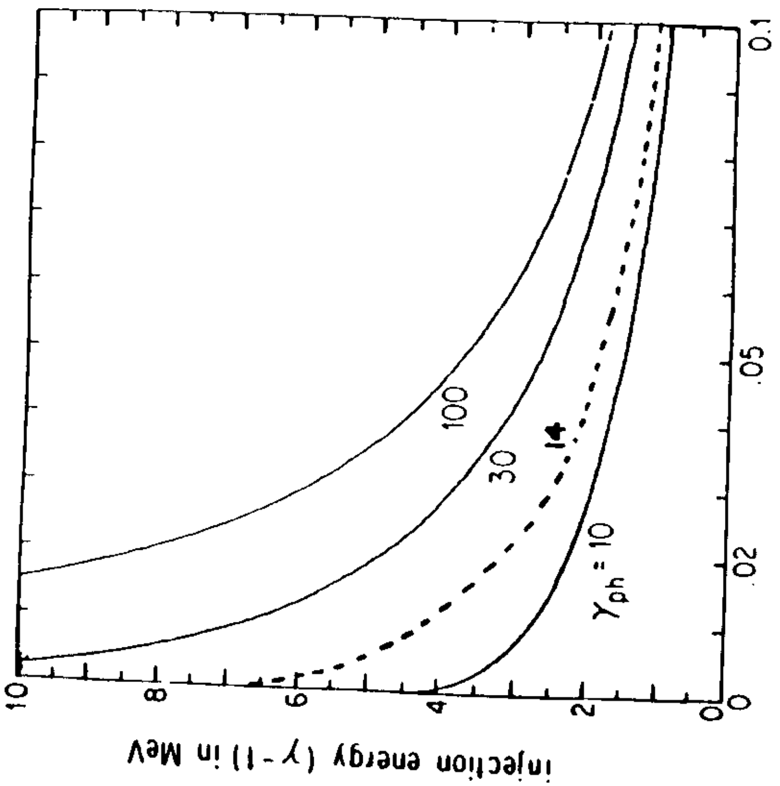
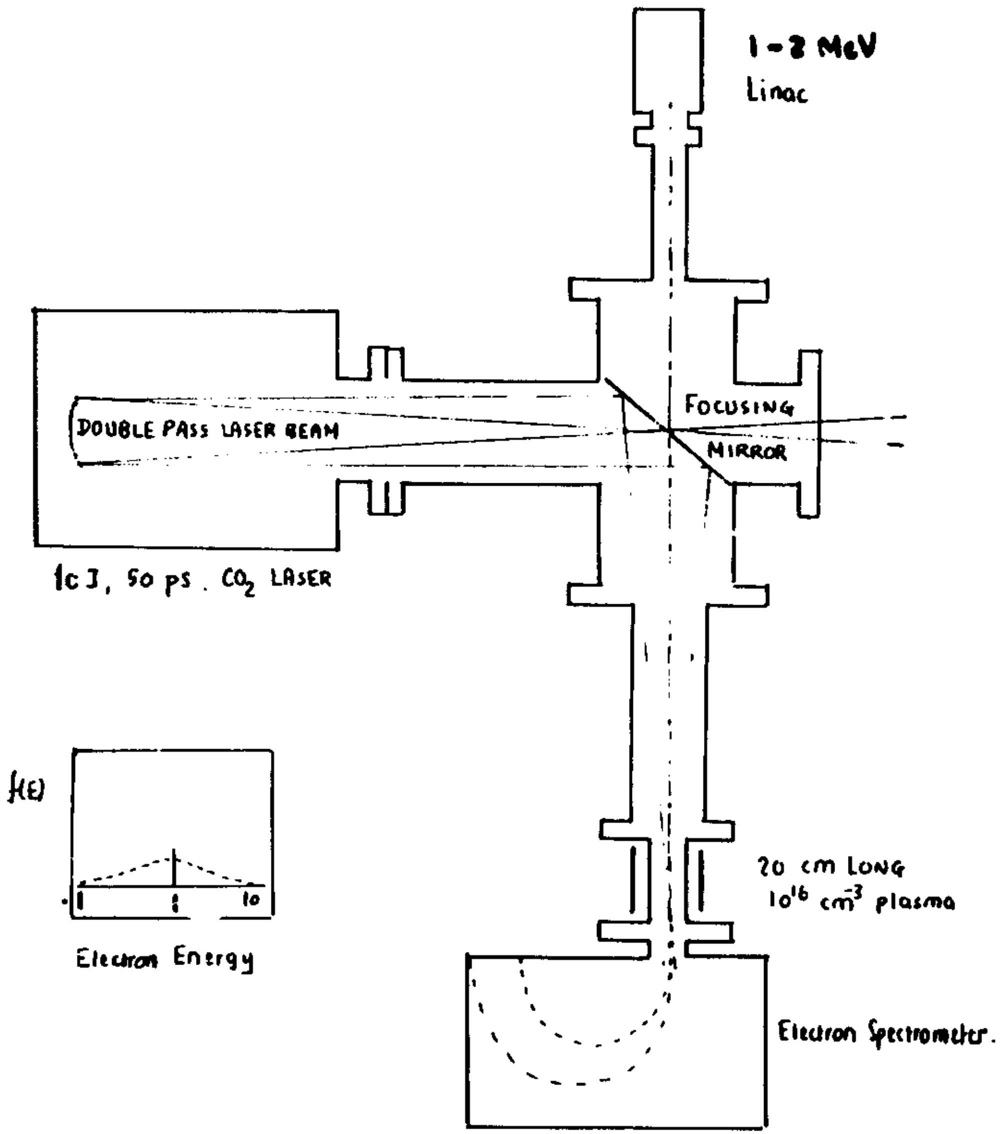


Fig. 1. Injection energy versus wave amplitude for plasma waves with different phase velocities.

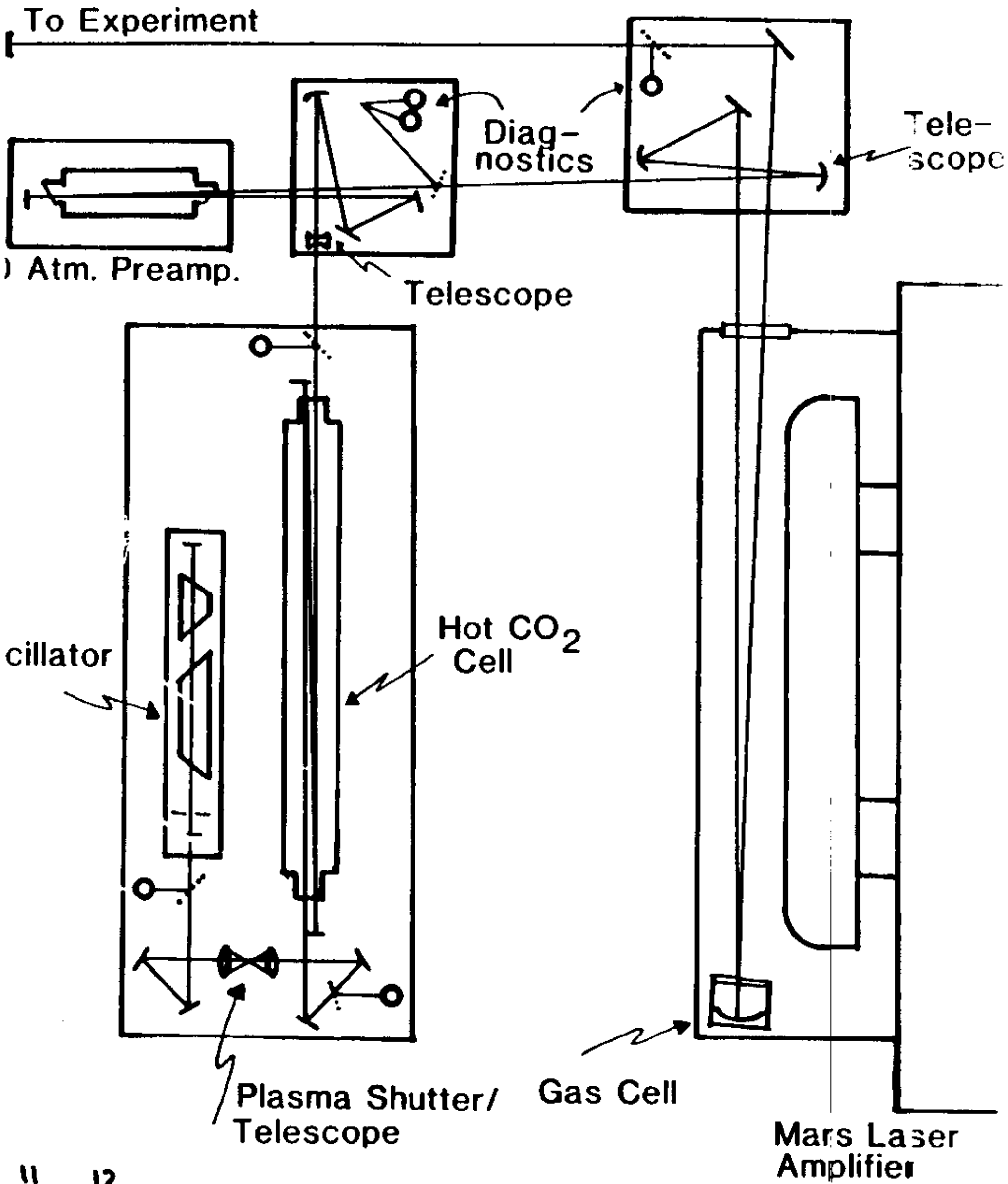
$\varepsilon = \frac{1+\varepsilon'^2}{2\varepsilon'}$

$\varepsilon' = \varepsilon + 1/\gamma_{ph}$

PROPOSED BEAT WAVE ACCELERATION EXPERIMENT (1986-1989)



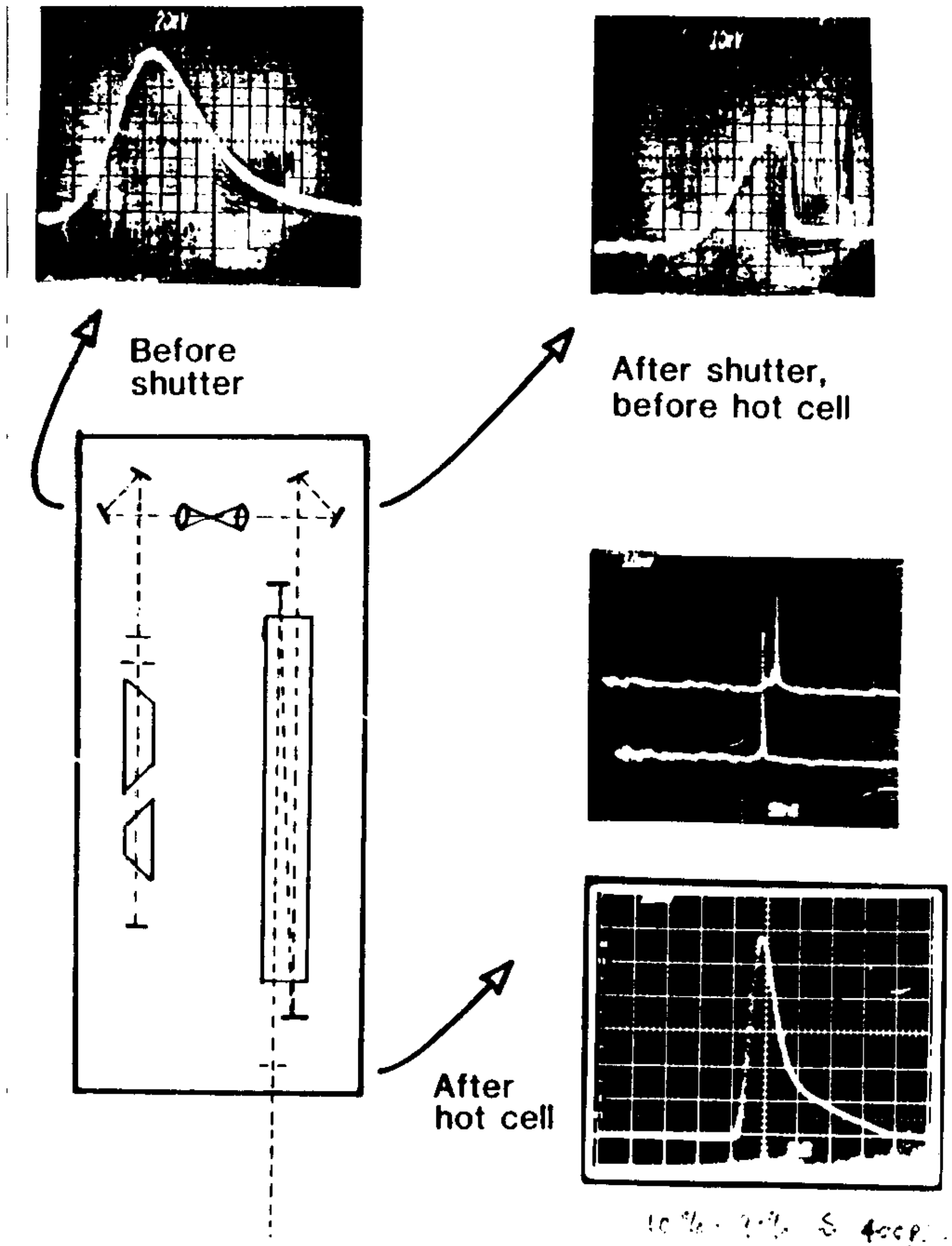
MARS LASER SYSTEM



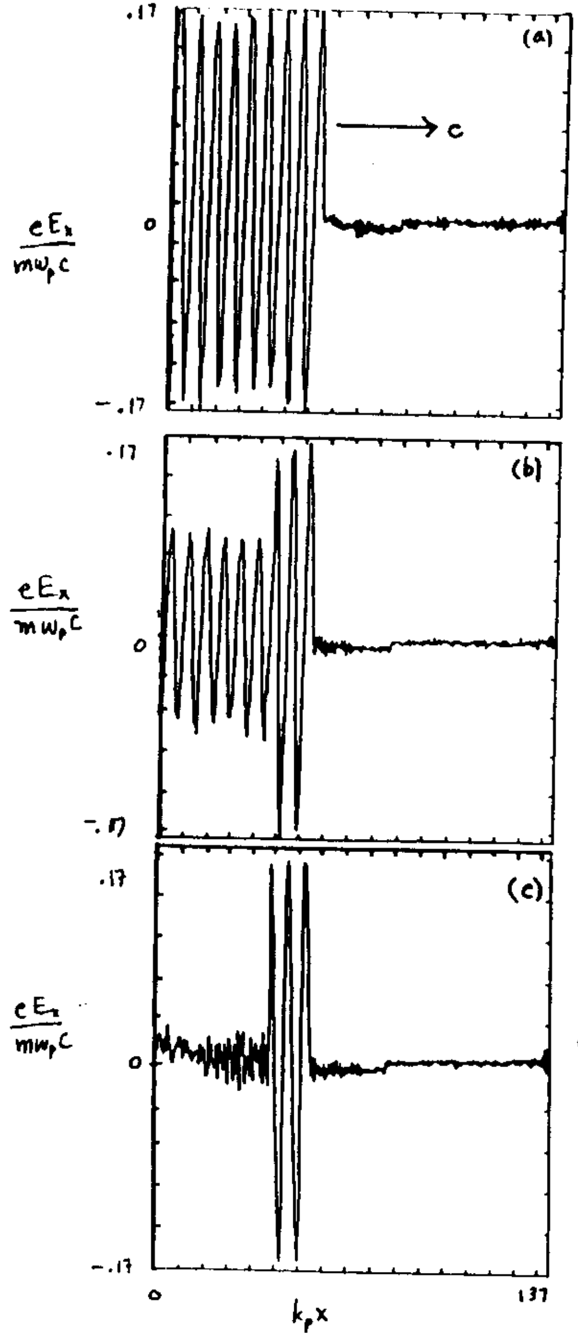
0^{11} - 10^{12} W

50 - 600 ps (Variable), Single or Duel frequency

OPTICAL FREE INDUCTION DECAY



Beam Loading Calculations in 1 Dimension.



$N_{t.b.} = 1$ particle

$\epsilon \cong 0\%$

$N_{t.b.} = 120$ particles

$\epsilon \cong 75\%$

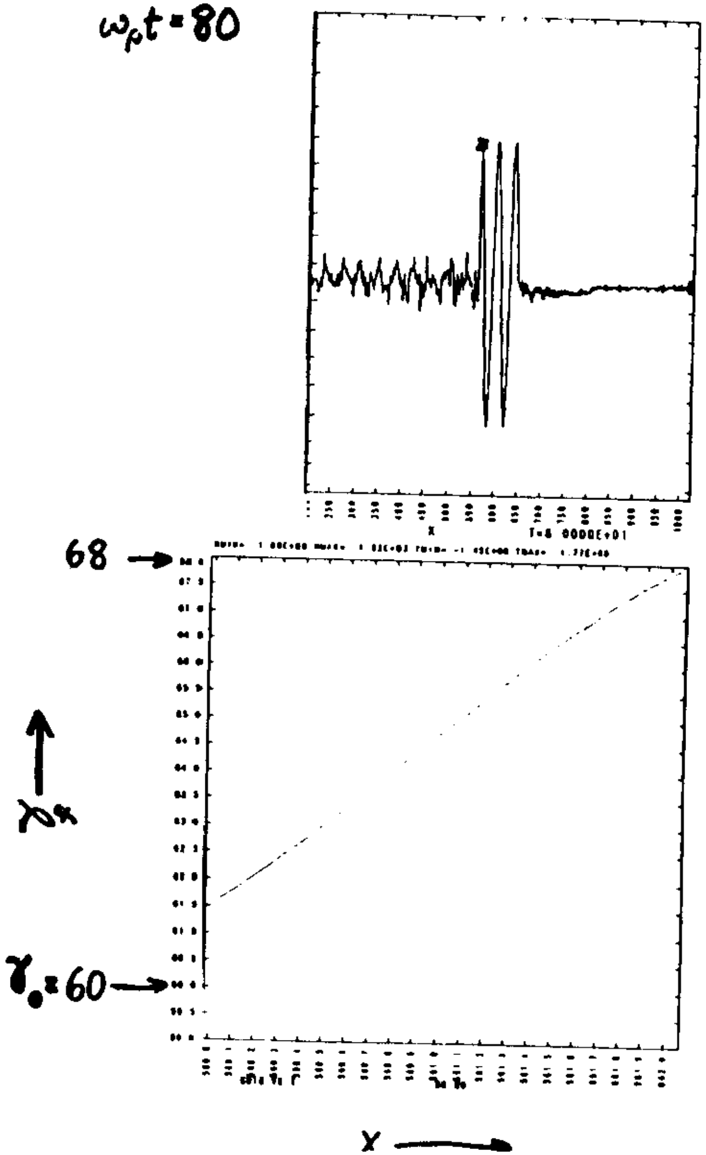
$N_{t.b.} = 240$ particles

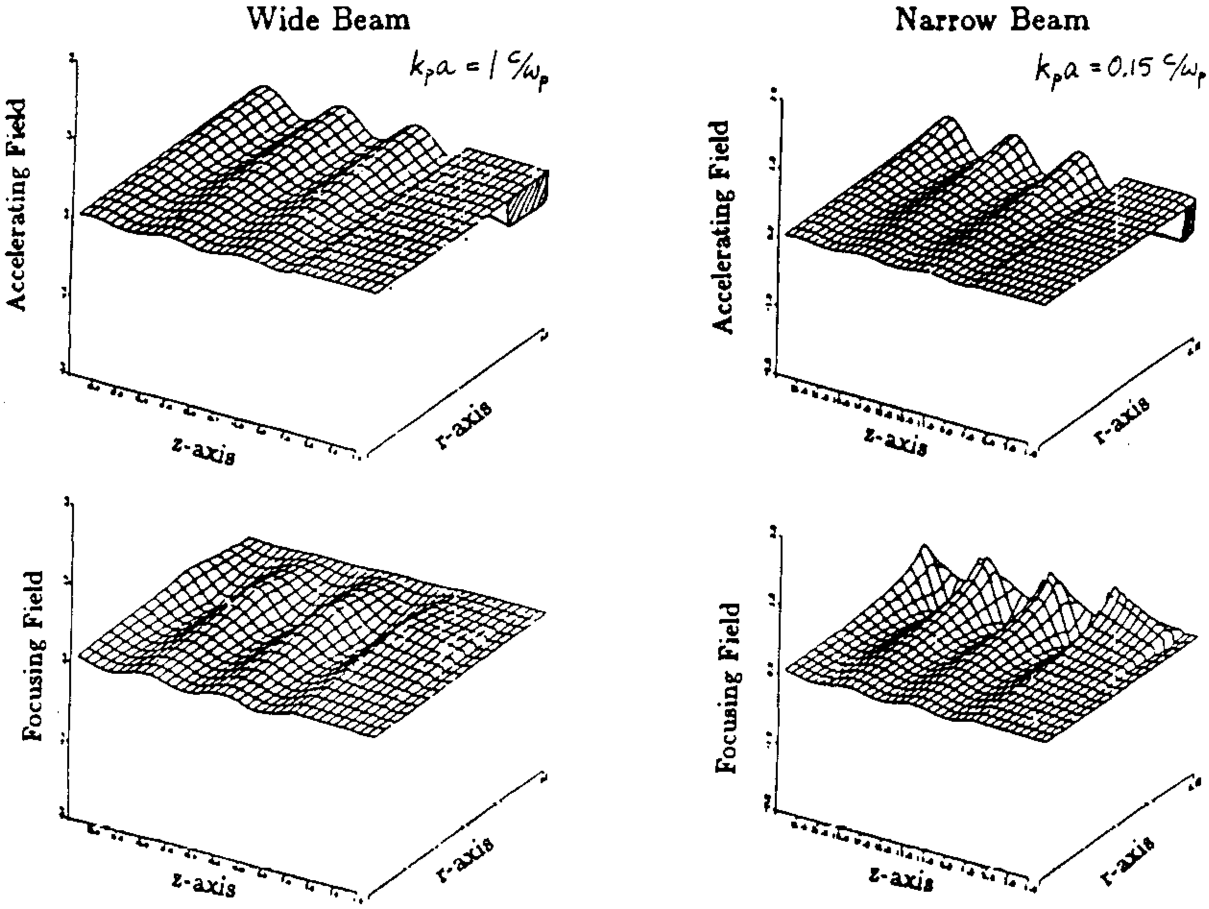
$\epsilon \cong 100\%$

Problems with this Scheme

(- too much ΔE)

$\omega_p t = 80$





Stability of the Driving and the Trailing Beams in the PWFA due to Weibel Instability, R vs. Z

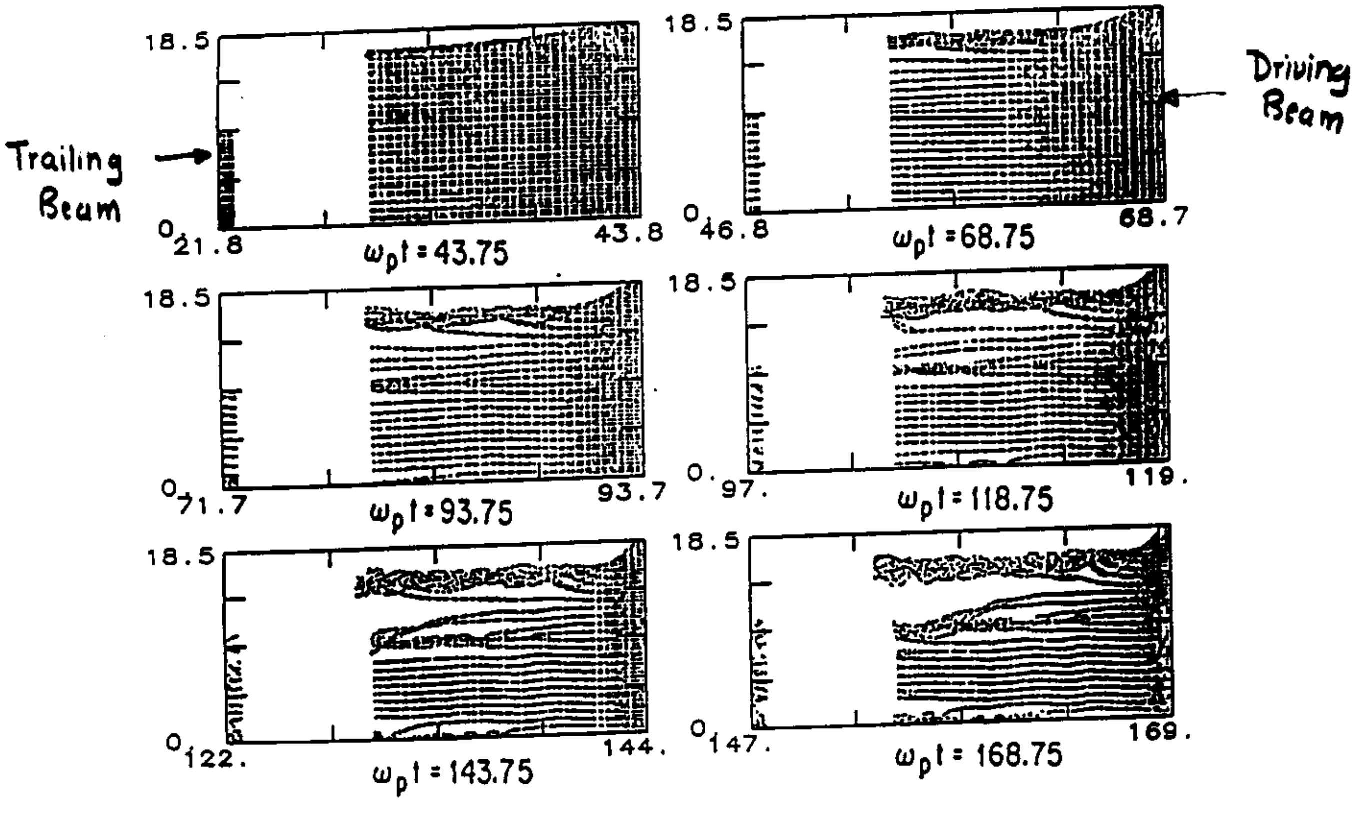


Fig 5

Suppression of the Weibel Instability by Introducing $kT_\perp$.

R VS. Z

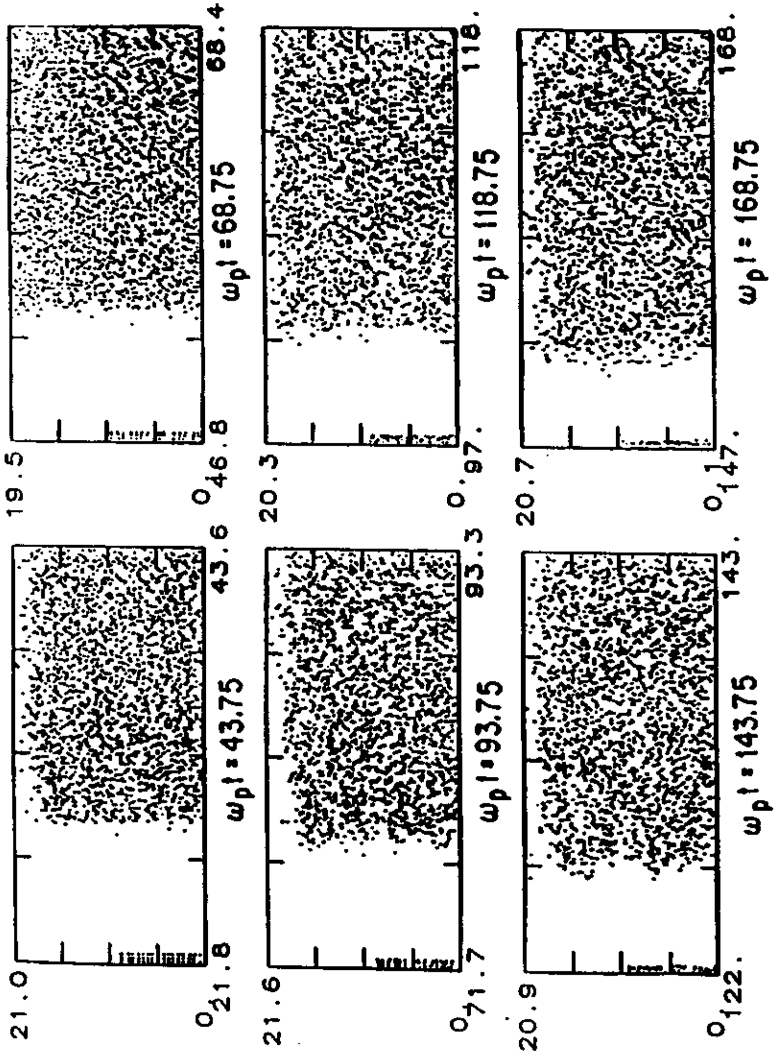
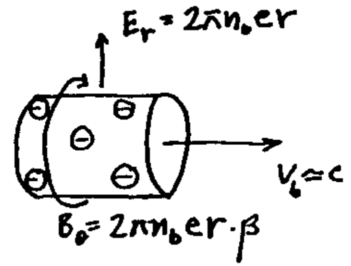


Fig 7

$kT_\perp \sim \frac{1}{4} \frac{n_b}{n_p} mc^2$ or for $\frac{n_b}{n_p} = 0.2$ $kT_\perp \sim 50$ keV

Plasma Lens: Physical Mechanism:

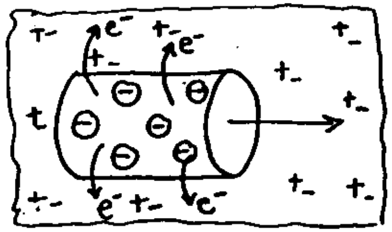
In vacuum:



$$F_r = E_r + \left(\frac{\vec{v}}{c} \times \vec{B}_\theta\right)_r = 2\pi n_b e r(1-\beta^2) \approx 0$$

$\therefore F_r \cong 0$.

In plasma:

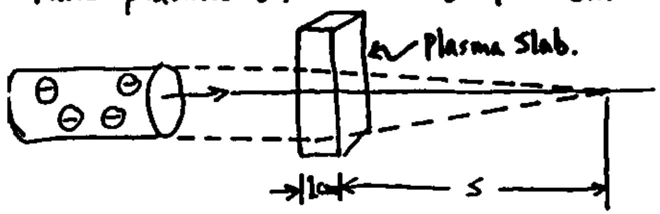


Plasma space charge neutralizes E_r, thus:

$$F_r = \left(\frac{\vec{v}}{c} \times B_\theta\right)_r \approx -2\pi n_b e r$$

For Example:

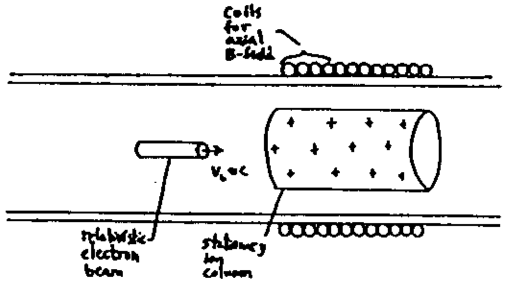
- SLAC-type beam : $n_b \cong 10^{15}$ cm^{-3}
- Take plasma of : $n_o = 10^{18}$ cm^{-3}



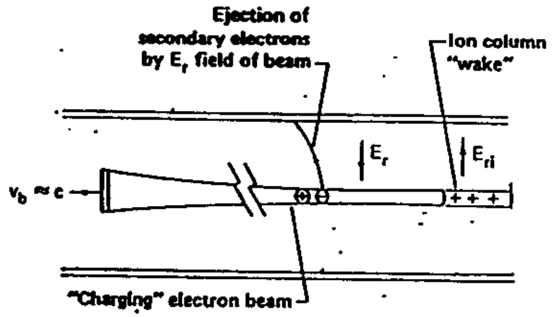
- Focusing Gradient: $F_r/r \simeq 2\pi e^2 n_b \simeq 15$ MG/cm
  (s = 10 cm)

Methods of Ion Column Creation

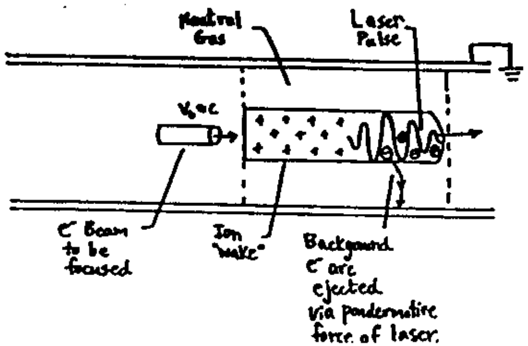
1. Ion Trap:



2. Briggs scheme:



3. Laser scheme:



Ion Column Focusing

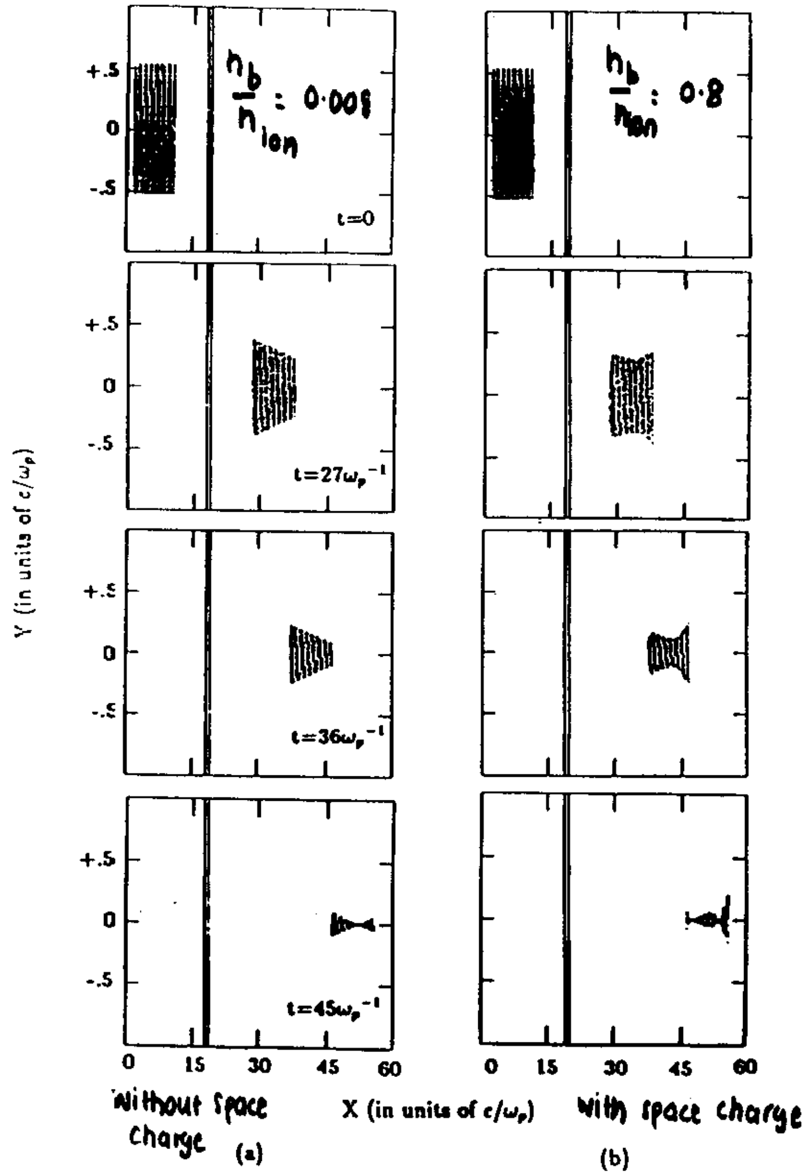


Fig. 2

MOTIVATION FOR PLASMA WIGGLERS:

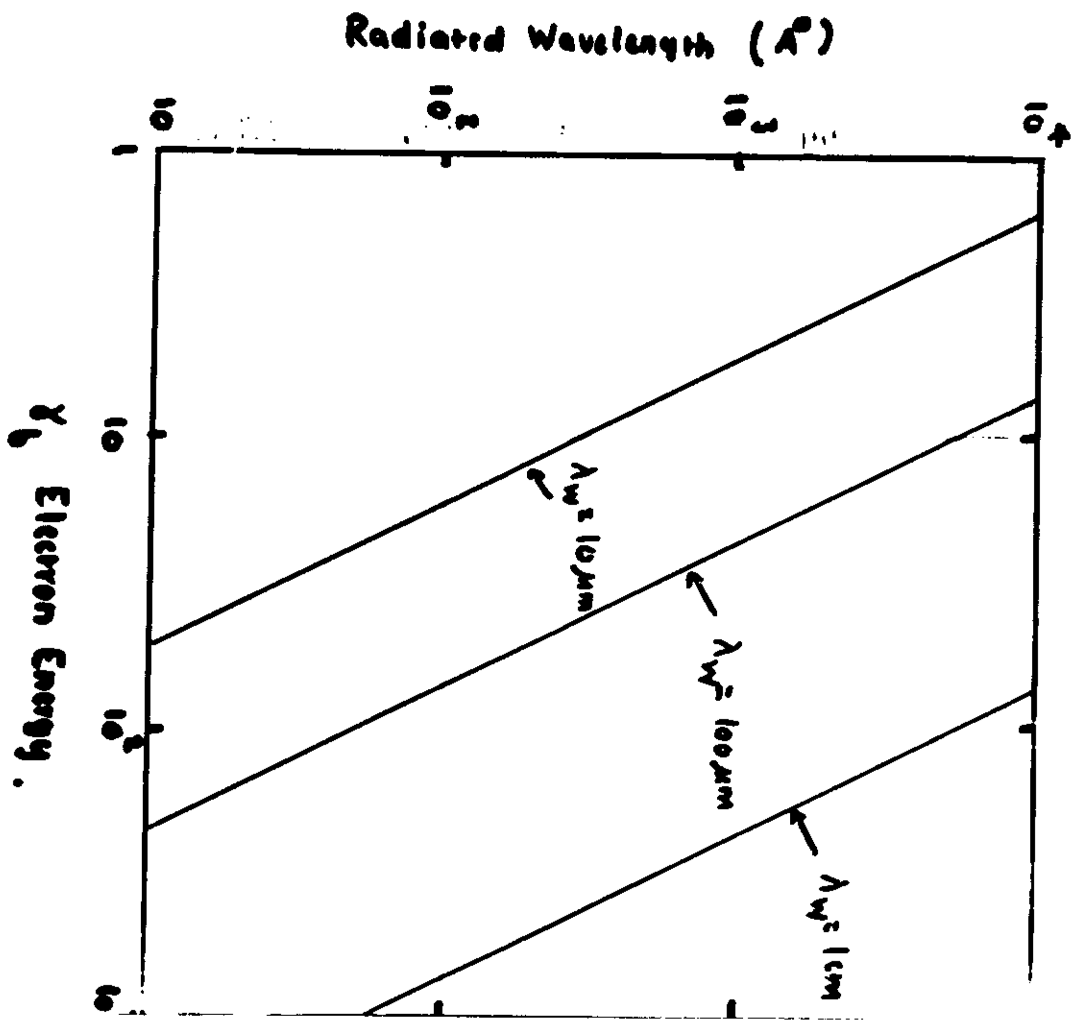
1. Large amplitude plasma waves currently produced for acceleration experiments (natural extension to inject e^- at other angles)

2. Typical wiggler wavelengths $\approx 30\mu - 1\,mm$
   - shorter than conventional : $\lambda_w \gtrsim 1\,cm$
   - enables VUV/Soft X-ray w/ low energy beam: 10 MeV vs. GeV

3. Strong wiggler strength:

$$a_w \equiv \frac{eA}{mc^2} = \frac{eE}{m\omega c} \lesssim 1$$

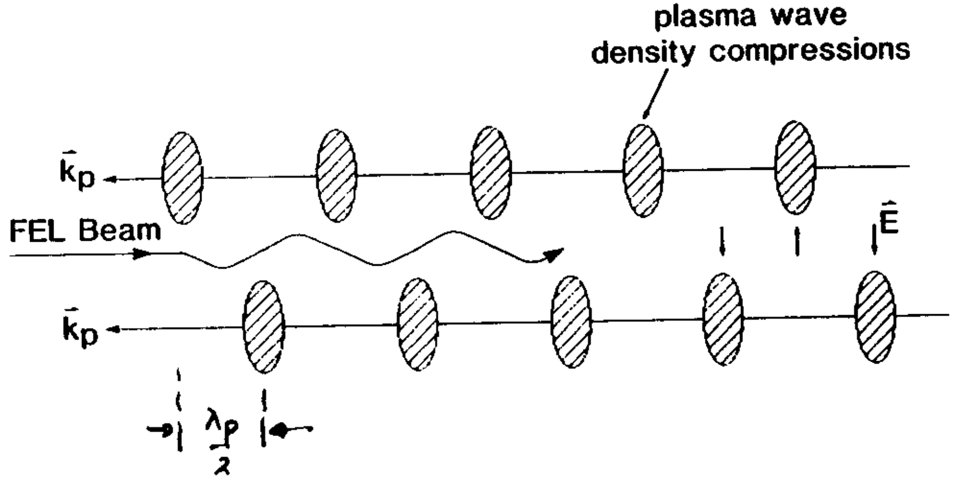
$$\Rightarrow B_{eff} = \frac{2\pi A}{\lambda_w} \lesssim 1 \text{ Megagauss at } \lambda_w \sim 100\mu$$



UNDULATOR TYPE	LAB FRAME	ELECTRON FRAME
Purely magnetic	N S N / S N S; $\omega_o = 0$, $k = k_w$	$\omega' = \gamma\beta k_w c$, $k' = \gamma k_w$
Electromagnetic	$\omega_o = k_o c$	$\omega' = \gamma\omega_o(1+\beta) = k'c$
Purely Electric (Plasma Wave)	E_y; $\omega = \omega_p$, $k_x = 0$	$\omega' = \gamma\omega_p$, $k' = \gamma\beta\omega_p/c$

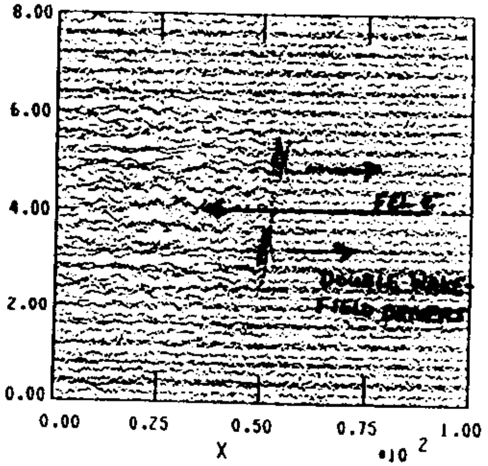
Equivalence of magnetic, e.m. and plasma wave undulators.

One Possible Geometry for a Plasma Wiggler

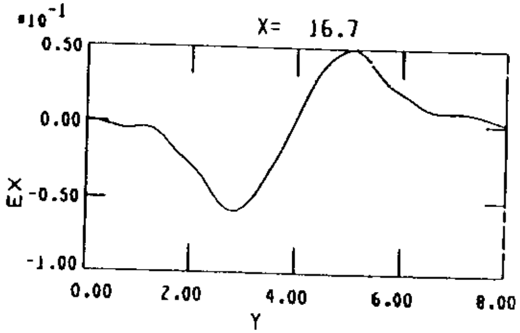


DOUBLE PLASMA WAVE WIGGLER:

- DOUBLES a_W
- SOLVES BLOWOUT PROBLEM

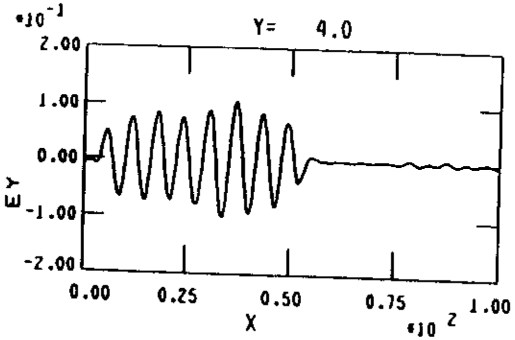


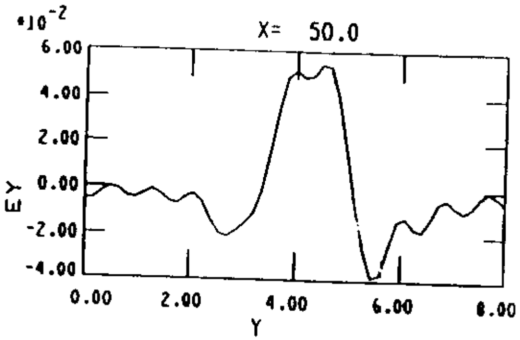
DOUBLE WIGGLER GEOMETRY



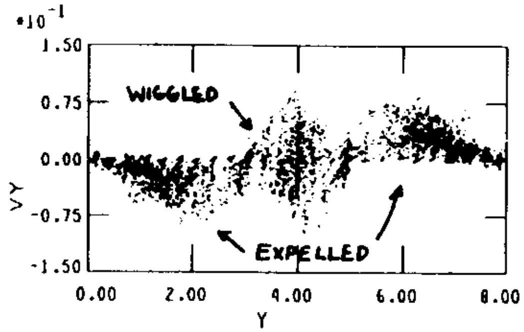
LONGITUDINAL FIELD: $\partial_y E_x^2 \Rightarrow$ FOCUSIN.

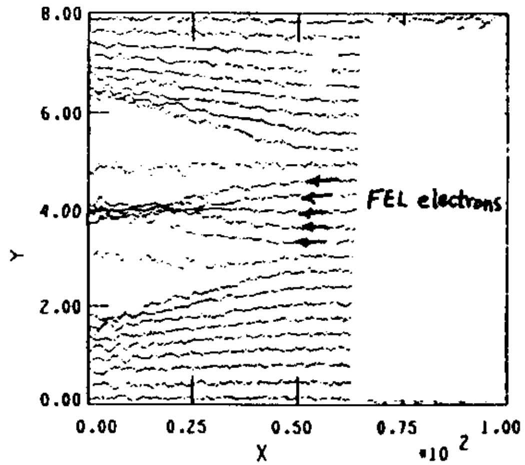
WIGGLER FIELD





BEAM TRAJECTORIES IN DOUBLE WIGGLER





CONCLUSIONS

1 Plasmas represent one extremum of the parameter space for building high gradient accelerators, ultra-strong focusing lenses for relativistic particles and ultra-short wavelength wigglers for synchrotrons

2 The concepts are basic.
The usual laser-plasma or beam-plasma instabilities are avoided by ultra short driver (laser pulse or electron bunch) that continually move into fresh plasma.

old saying : airplanes wouldn't fly if they didn't leave turbulence behind.

3 Lot of scope for doing theoretical work on nonlinear phenomena :

- What happens to nonlinear plasmons in the presence of ion fluctuations
- theory of Weibel and relativistic two stream