REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL 30 Sep 91 - 29 Dec 94

4. TITLE AND SUBTITLE
Harmonic Gyrotron Amplifiers and Phase Locked Oscillators

5. FUNDING NUMBERS
~~61102F~~
6223/4N

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Maryland
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College Park, MD 20742

8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 95 - 0250

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-0001

10. SPONSORING MONITORING AGENCY REPORT NUMBER
AFOSR-91-0390

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

SEE FINAL REPORT ABSTRACT

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED

FINAL REPORT

30 September 91 - 29 September 94

for

Harmonic Gyrotron Amplifiers and Phase-Locked Oscillators

AFOSR Grant AFOSR-91-0390

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Submitted to
Dr Robert J. Barker
AFOSR/NE

MARYLAND HIGH POWER SOURCES

THEORY GROUP

* **Faculty**

    T. Antonsen Jr.

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* **Post Docs**

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    G. Saraph

    C. Liu

* **Undergraduate Students**

    S. Rajapatirana

    Y. Lu

Research Area

Mode Competition and Multi-Frequency effects in high power fast wave devices

Specific Applications:

1. High power gyrotrons for plasma heating
2. Parametric Mode interactions in harmonic gyrotrons
3. Multi-frequency effects in fel oscillators
4. Modeling of harmonic gyroklystrons, phase locked gyro oscillators, and gyro-twystrons

NONLINEAR SIMULATION OF HIGH POWER GYROTRONS

RESEARCH TOOL:

*Time dependent multi-mode simulation code (MAGY)

CODE FEATURES:

*Axial RF field profile determined self-consistently

*Time dependent

*Multi-Mode (frequencies are equally spaced)

*Realistic boundary conditions

*AC space charge

*DC space charge (voltage depression)

*Energy and Pitch angle distributions for incoming beam

*Window reflection and delay

*Non zero beam rise time

*Mode coupling due to non uniform wall radius

THEORETICAL APPROACH

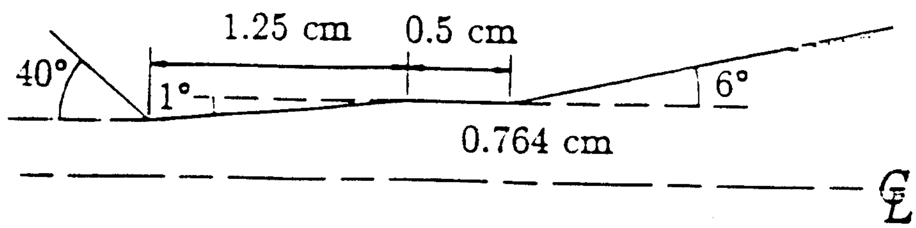
- Radiation field is expanded in transverse modes $\mathrm{TE}_{\ell p}$

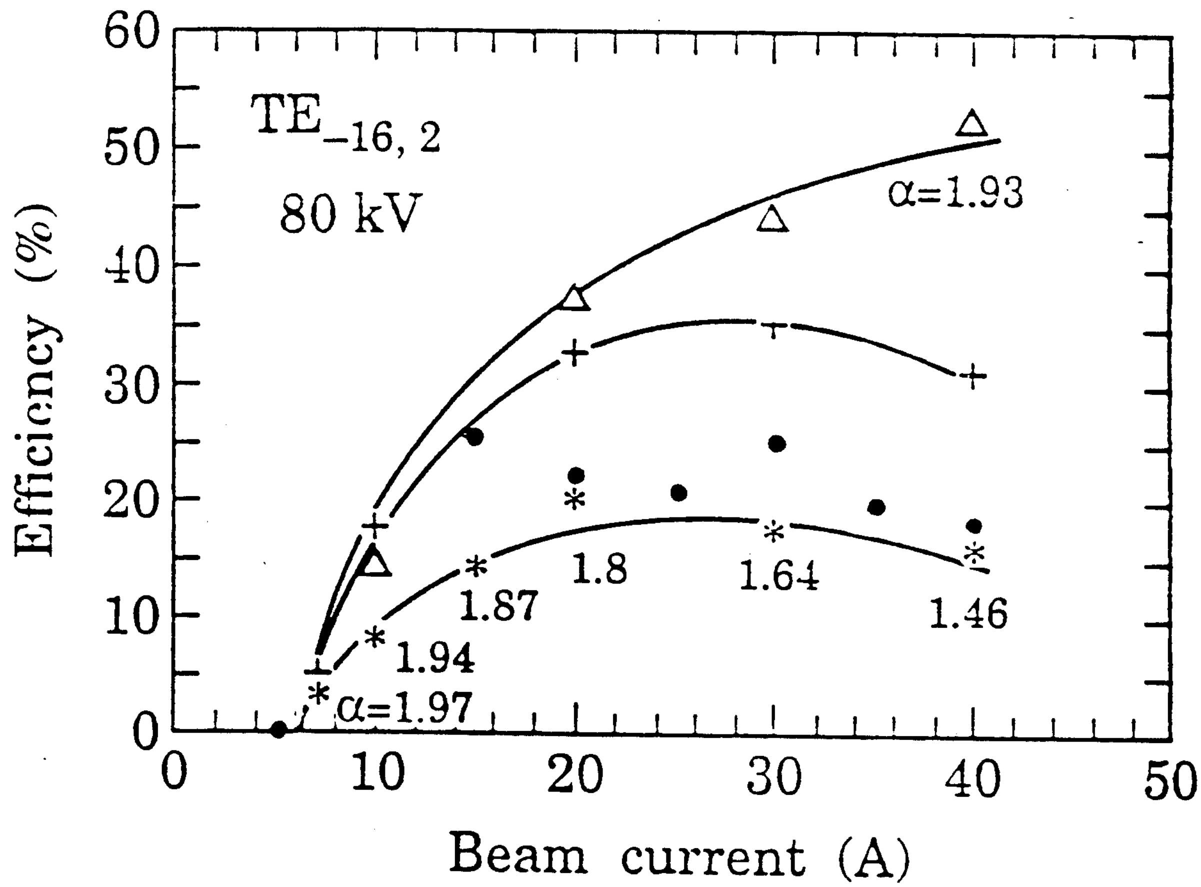
$$E(r,\phi,z,t) = \sum_{\ell p} \frac{c}{\omega_{\ell p}} E_{\ell p}(z,t)\exp(-i\omega_{\ell p}t)\hat{e}_z \times \nabla(J_\ell(k_{\ell p}r)e^{i\ell\theta}) + c.c.,$$

- Particle trajectories are followed in prescribed fields, AC beam current calculated

- Axially dependent field profile $E_{\ell p}(z,t)$ advanced in time.

SIMULATION OF MIT SHORT CAVITY





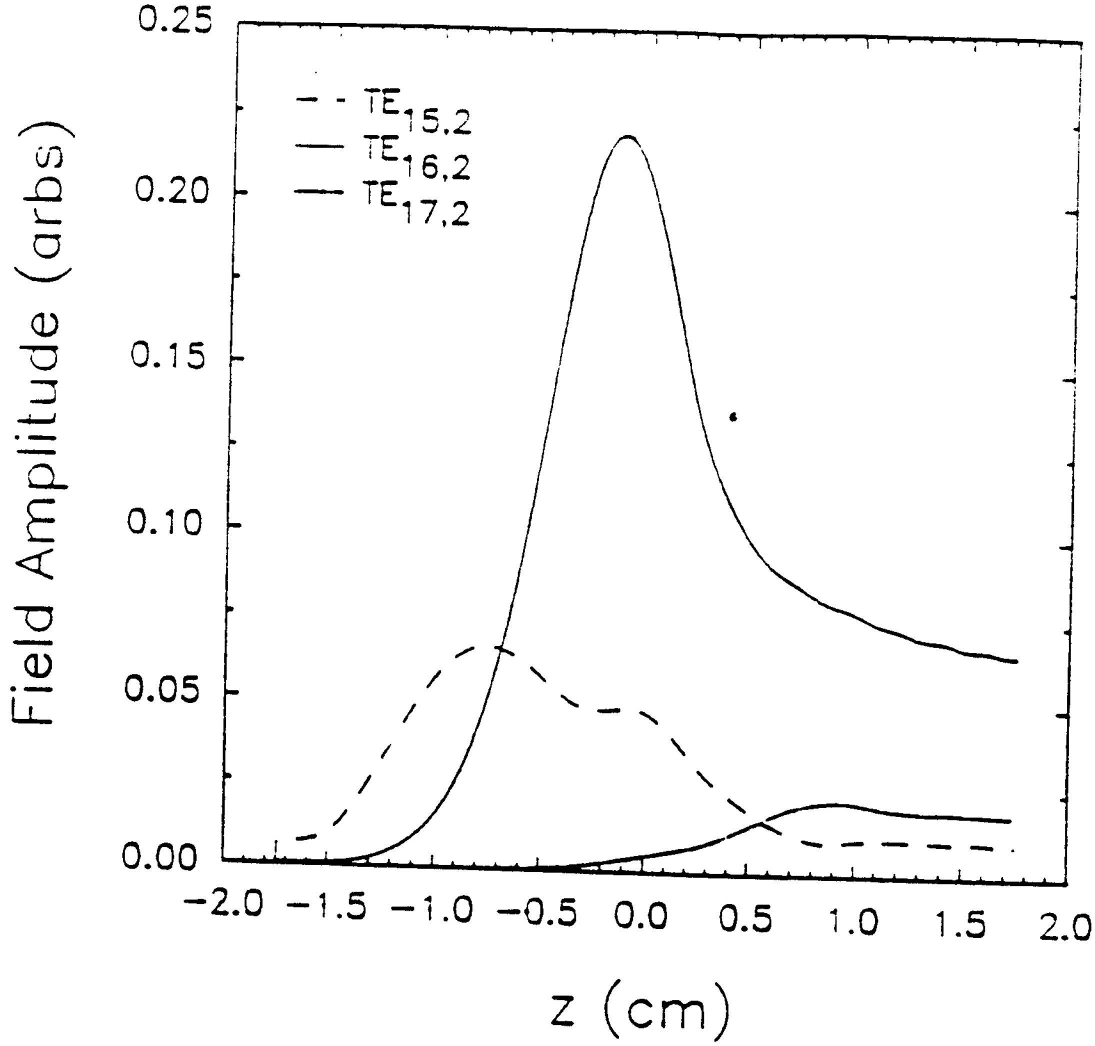
Δ : Single mode simulations with fixed α (=1.93).

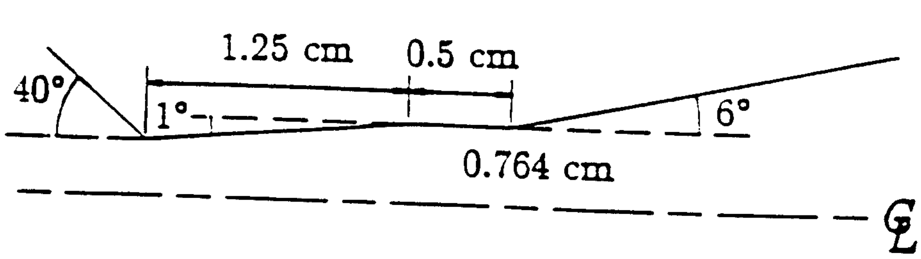
+ : Single mode simulations with varying α.

∗ : Multimode simulations with varying α.

• : Experimental measurements.

AXIAL FIELD PROFILES

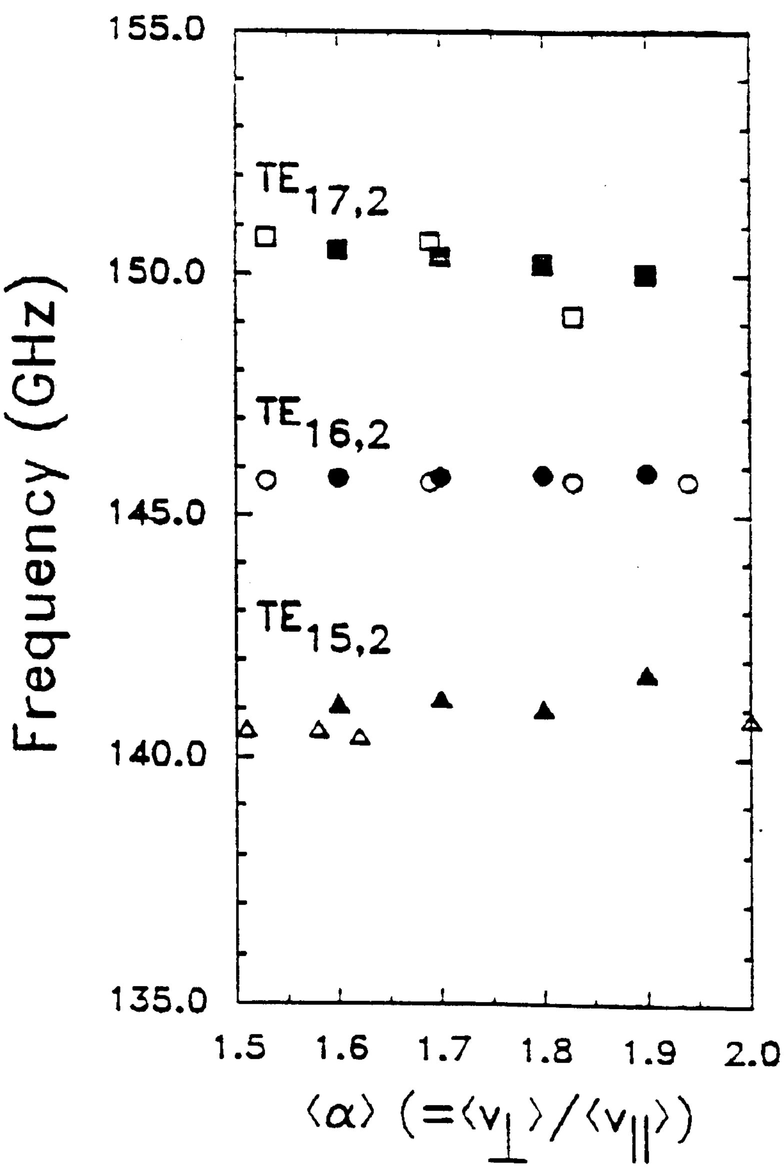




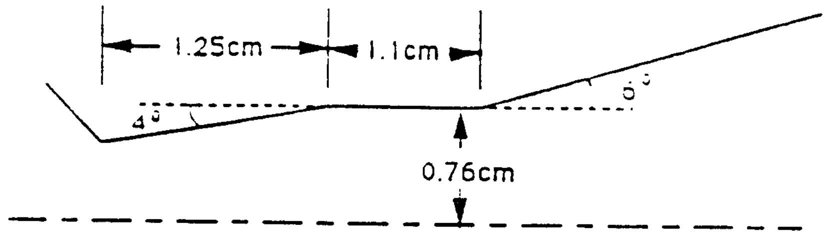
EXPERIMENTAL MEASUREMENT OF SIDEBANDS AT MIT

W.C. Guss, M.A. Basten, K.E. Kreischer, R.J. Temkin, T.M. Antonsen Jr., S.Y. Cai, G. Saraph, and B. Levush

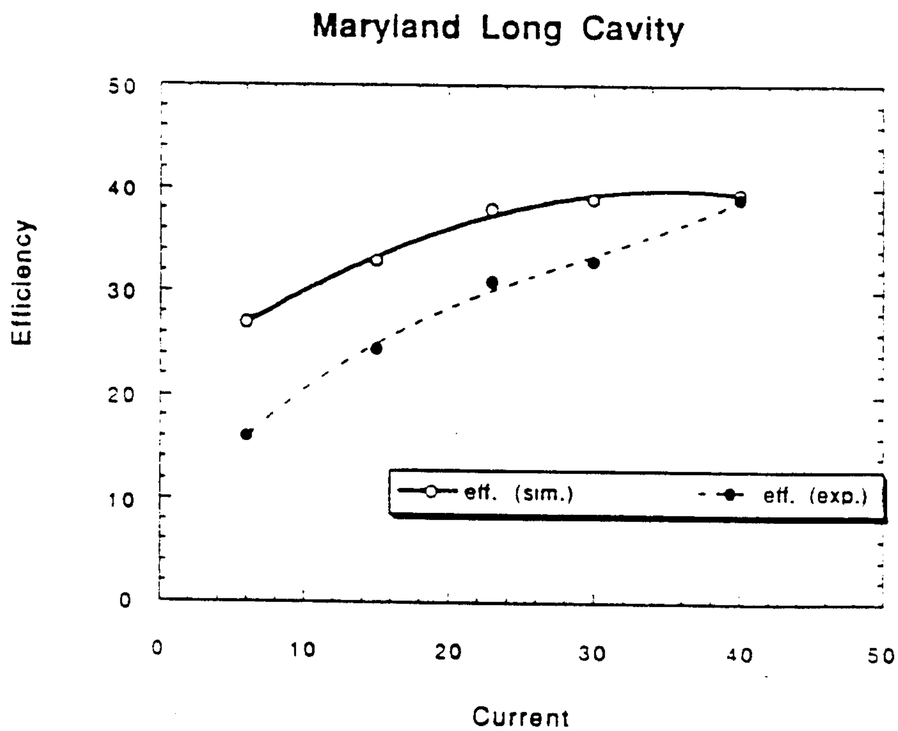
PREDICTED AND MEASURED MODE FREQUENCIES



MARYLAND LONG CAVITY



EFFICIENCY VS. CURRENT



Guss, Basten, Kreischer, Temkin, Antonsen, Cai, Saraph, and Levush, to be published in proceedings of IRMW

PARAMETRIC MODE COUPLING IN HARMONIC GYROTRONS

Ph. D. Thesis

Girish Saraph

PARAMETRIC INSTABILITY

Three cavity modes: $TE_{\ell_1 p_1}$, $TE_{\ell_2 p_2}$, and $TE_{\ell_3 p_3}$

The cyclotron resonance criteria is given by,

$$\frac{\omega_1}{s_1} \approx \frac{\omega_2}{s_2} \approx \frac{\omega_3}{s_3} \approx \frac{\Omega_0}{\gamma}$$

The **resonance criteria for the parametric instability** are as follows:

(a) For the harmonic numbers: $s_3 = s_1 + s_2$.

(b) For the azimuthal mode indices: $l_3 = l_1 + l_2$.

(c) For the angular frequencies: $\omega_3 \approx \omega_1 + \omega_2$,

Two **characteristic features** of the parametric instability are as follows:

(a) Three modes are phase-locked together .

(b) When only one mode has high amplitude then the small signal gains of the other two modes match.

When the three modes are parametrically coupled, then different types of mode interactions can take place, *viz.* **parametric excitation, decay of one or two modes, co-existence of three modes,** or **cyclic mode hopping** between the three modes.

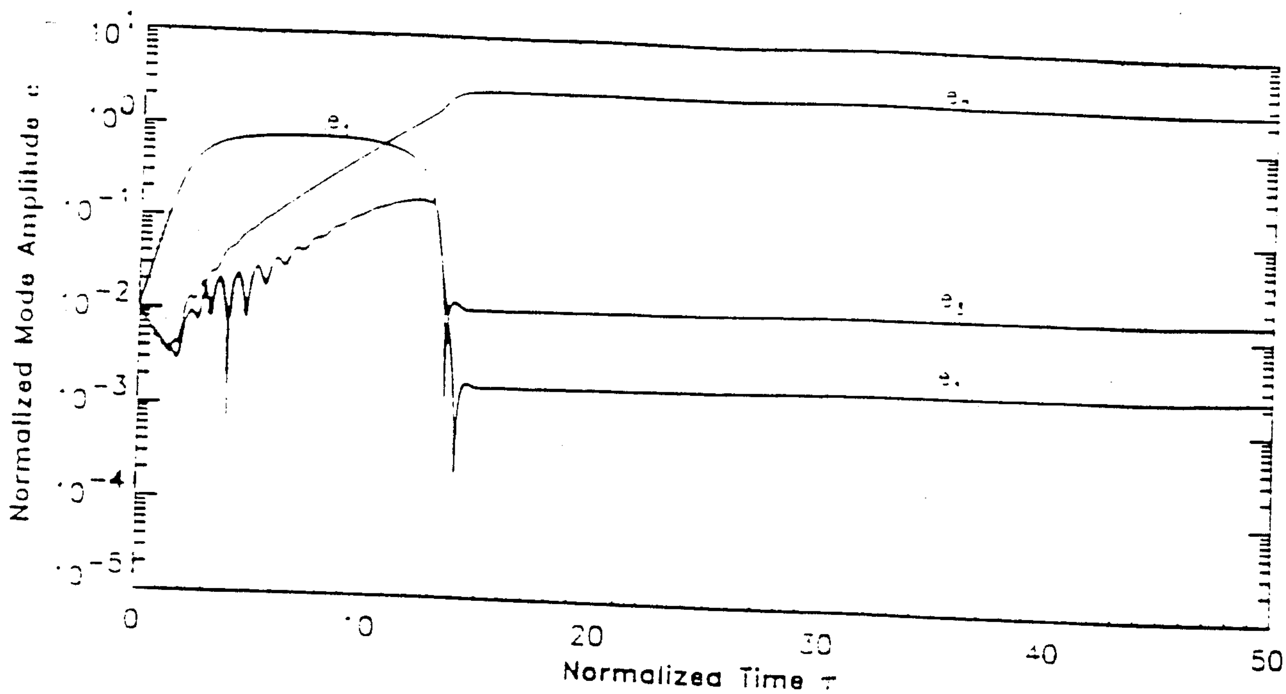
Notation used:

Mode 1 : $TE_{\ell_1 p_1}$ at the fundamental frequency ($s_1 = 1$)

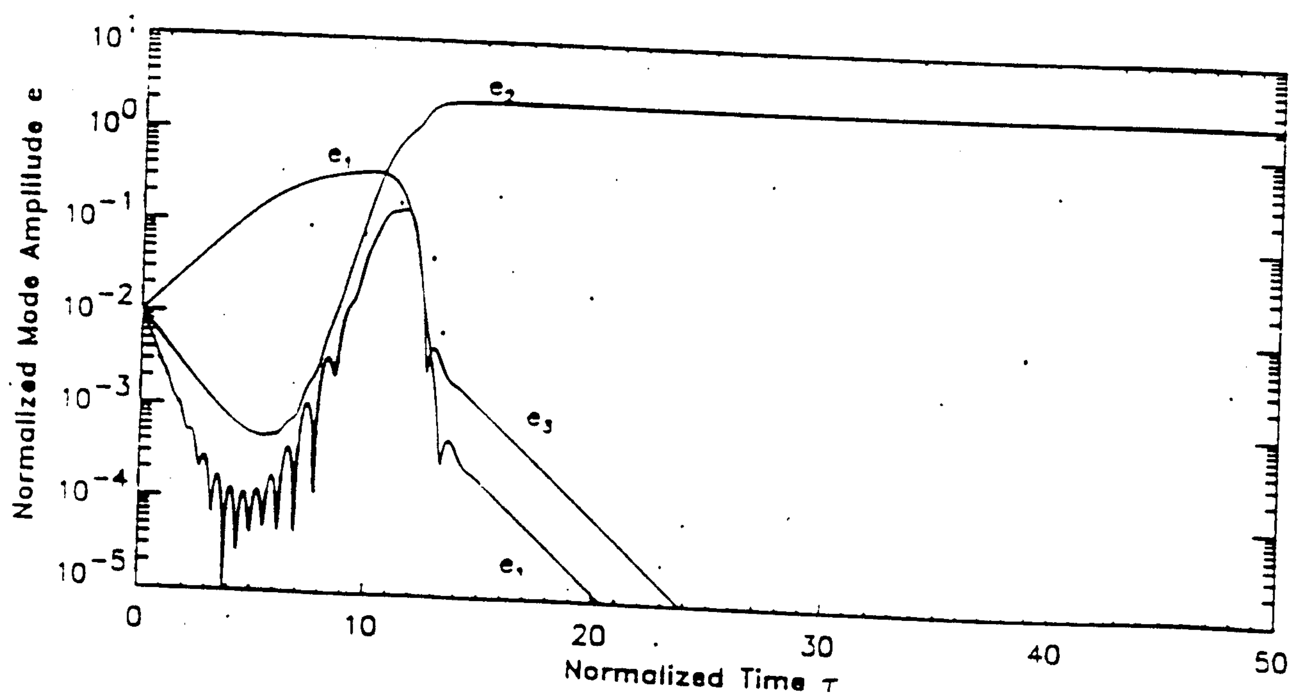
Mode 2 : $TE_{\ell_2 p_2}$ at the second harmonic frequency ($s_2 = 2$)

Mode 3 : $TE_{\ell_3 p_3}$ at the third harmonic frequency ($s_3 = 3$)

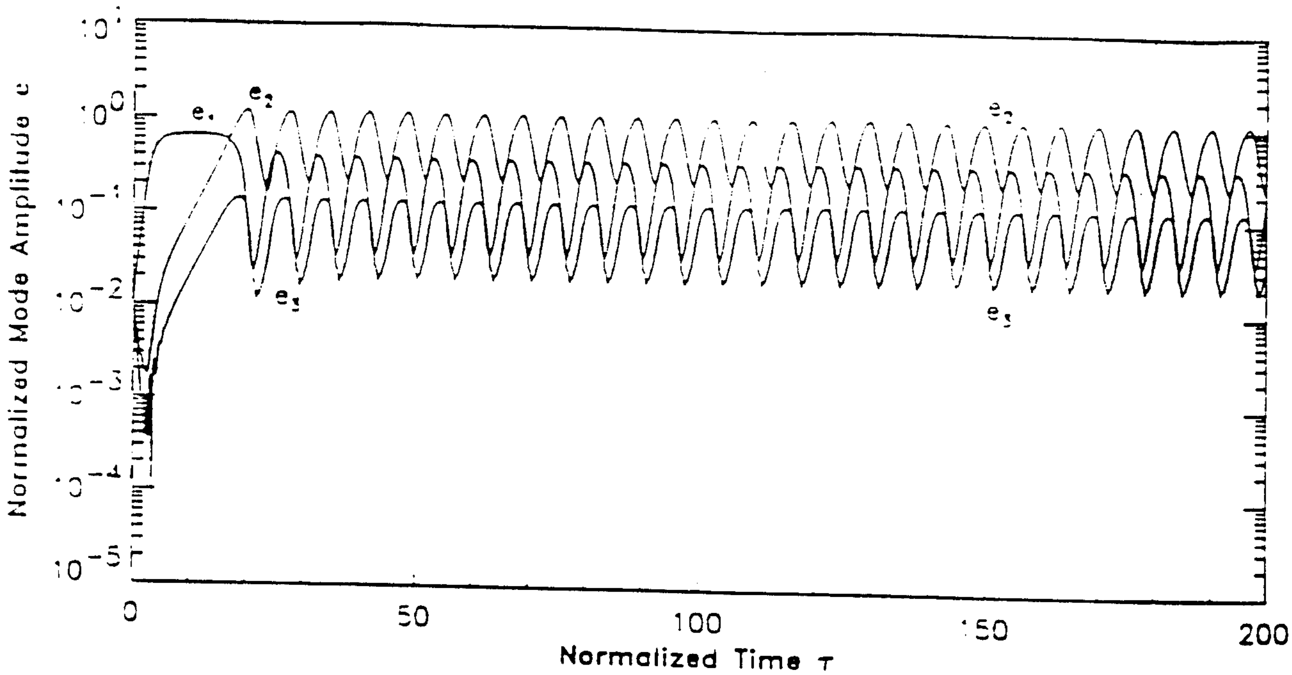
CO-EXISTENCE OF THREE MODES

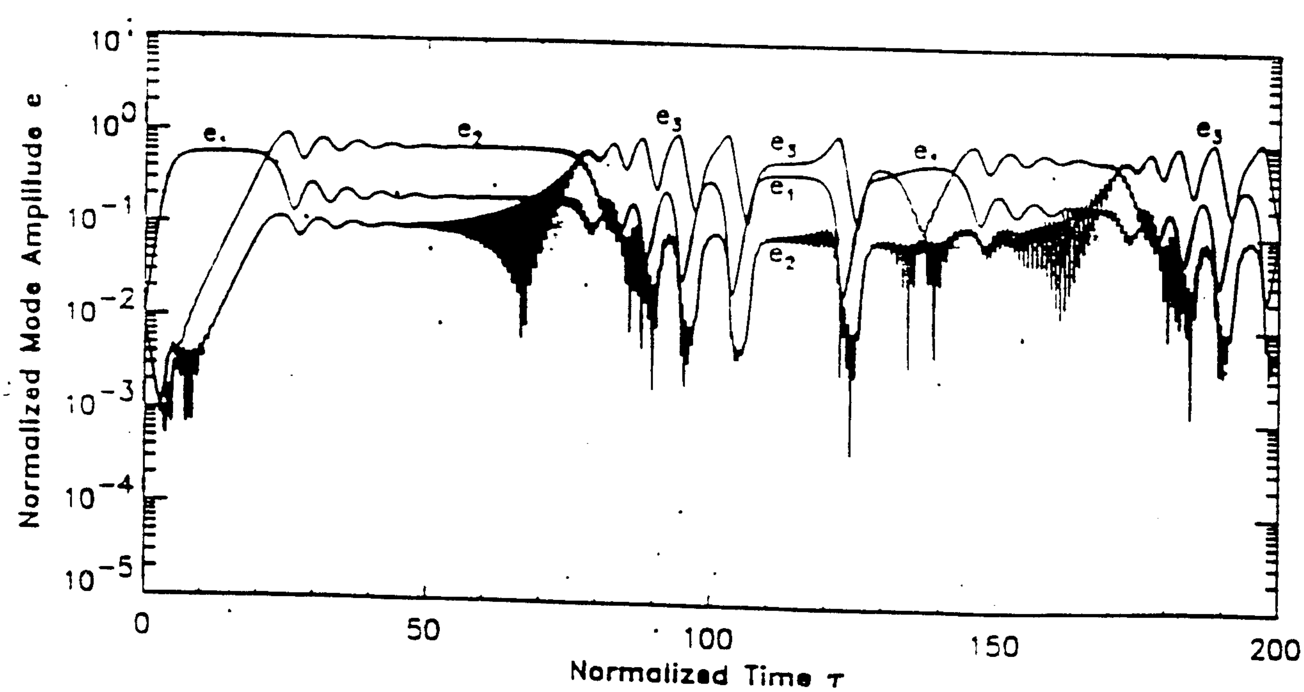


PARAMETRIC EXCITATION OF SECOND HARMONIC

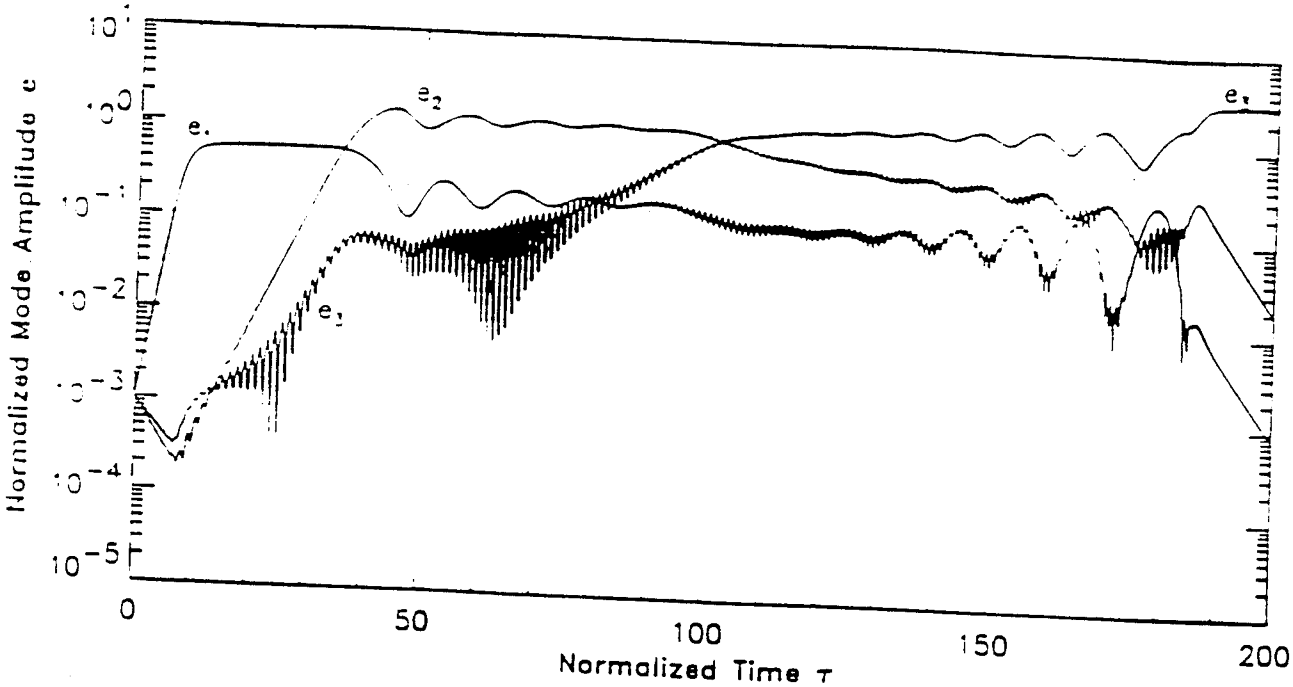


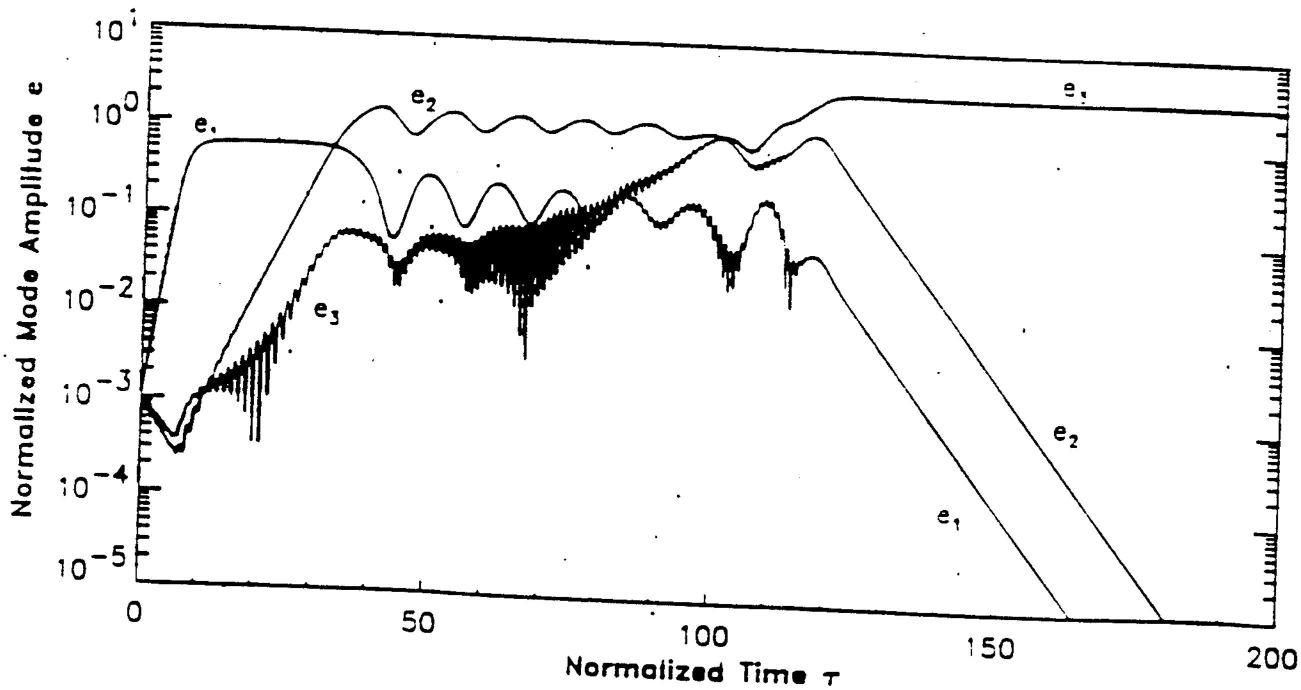
CYCLIC MODE HOPPING



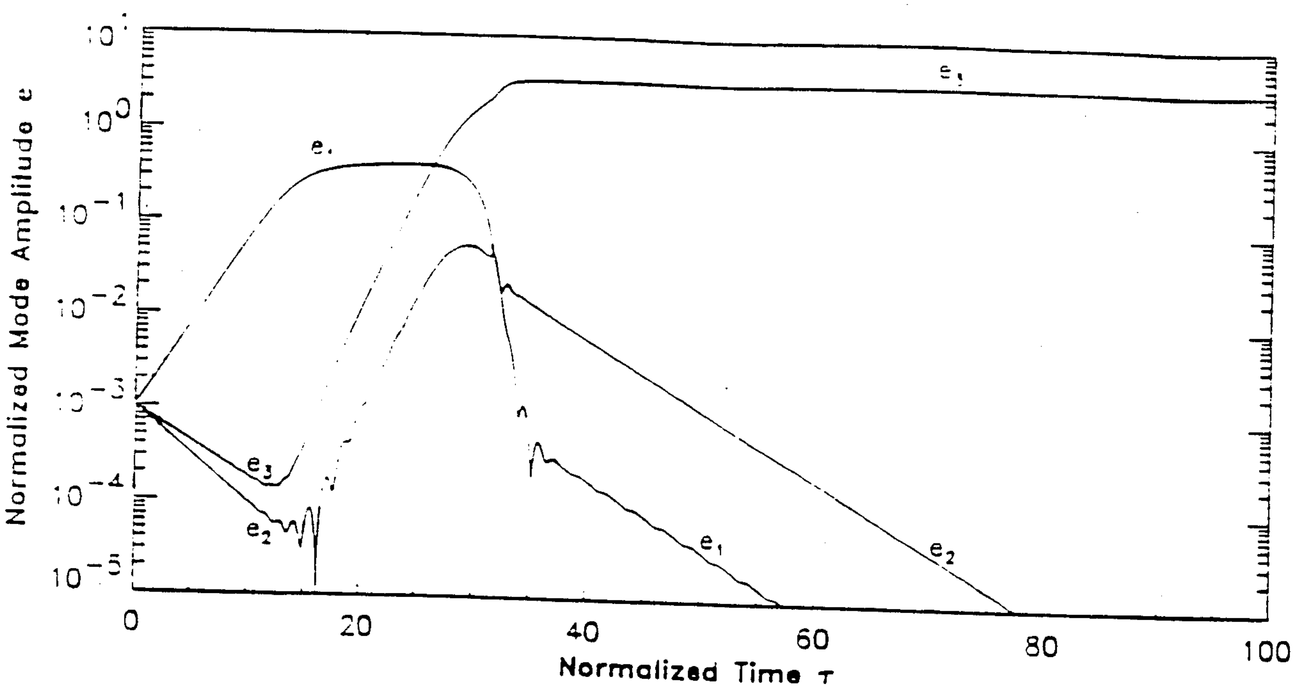


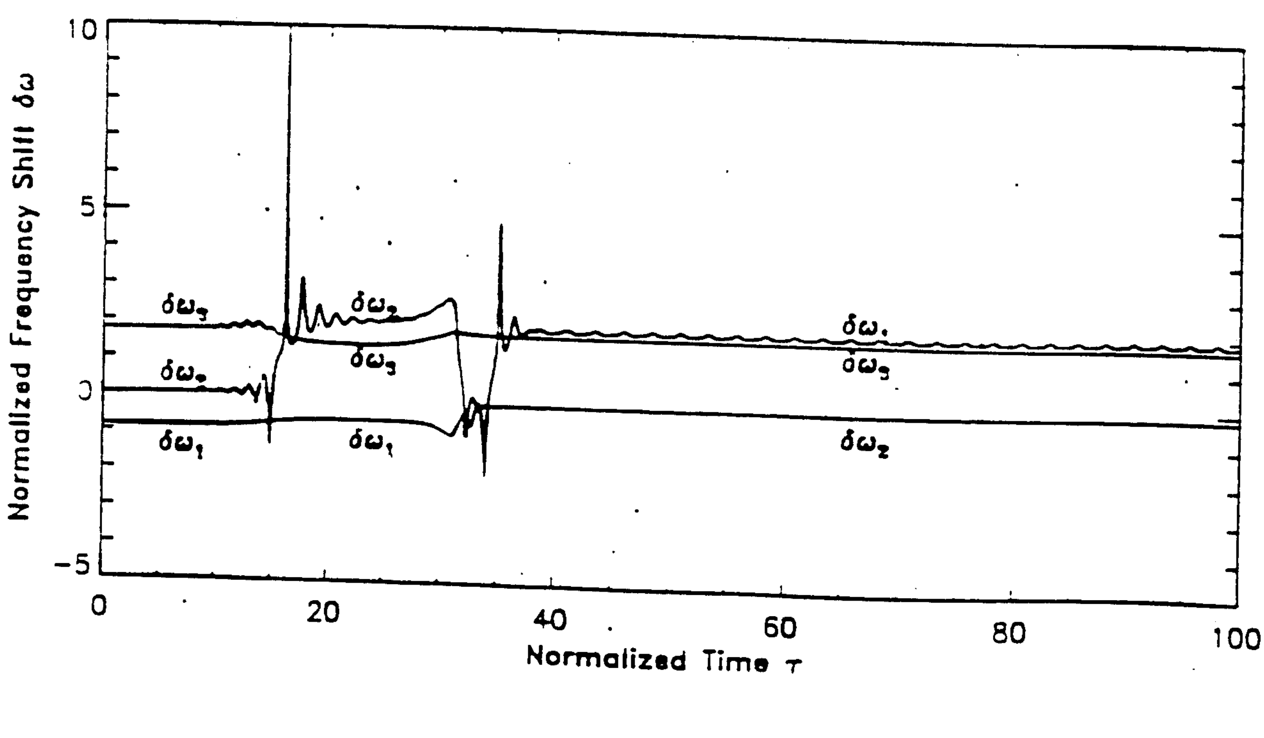
PARAMETRIC EXCITATION OF THIRD HARMONIC



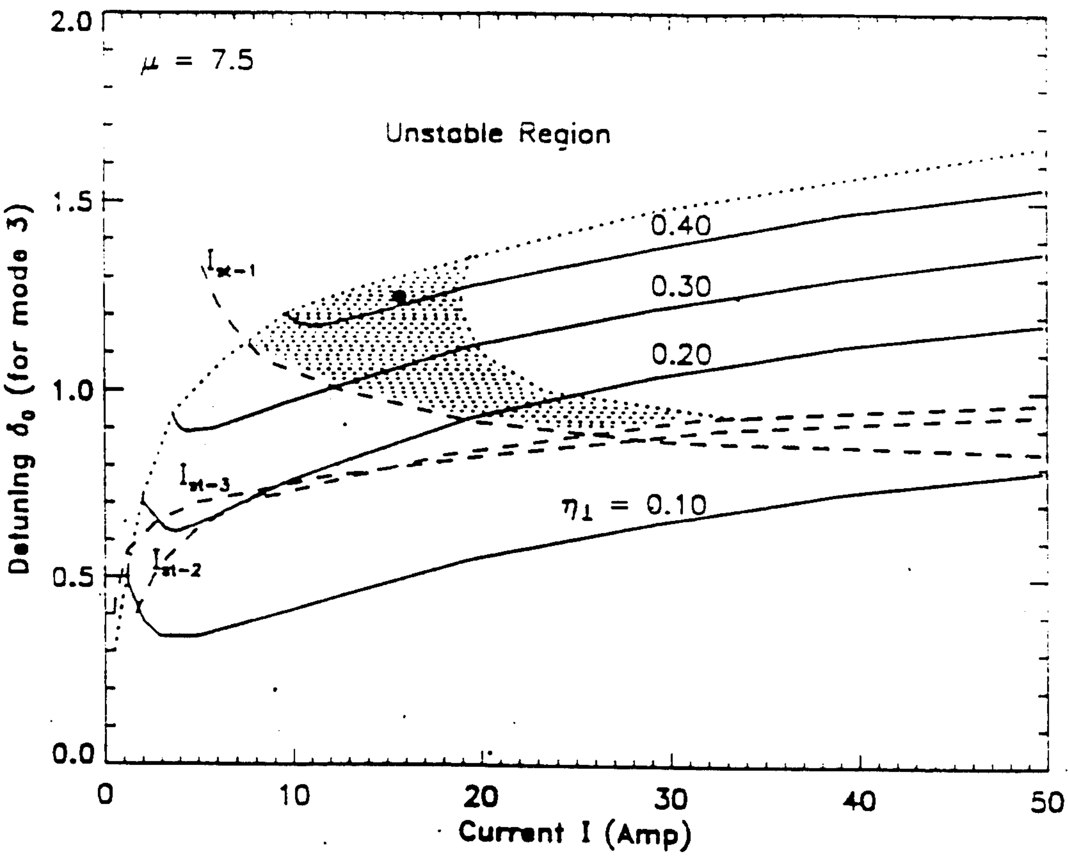


PHASE-LOCKING OF MODES





REGION OF PARAMETRIC EXCITATION OF A THIRD HARMONIC AT 94 GHZ



DESIGN OF A THIRD HARMONIC GYROTRON AT 94 GHZ

Mode 1 : $TE(3,1)$ at $s_1 = 1$

Mode 2 : $TE(1,3)$ at $s_2 = 2$

Mode 3 : $TE(4,3)$ at $s_3 = 3$

Selected Quantities:

Wall Radius $r_w = 0.65\ cm.$

Beam Radius $r_b = 0.42\ cm.$

Quality Factors: $Q_1 = 300.$

$Q_2 = 1200.$ $\quad Q_3 = 2700$

Normalized Parameters:

$\mu = 7.5.$ $\quad t_p = 86.$ $\quad \hat{I}_1 = 230.$

$\delta = 0.7.$ $\quad e_3 = 3.18.$ $\quad \eta_\perp = 0.412$

Corresponding Physical Quantities:

Interaction Length $L_c = 4.14\ cm$

Operating Frequency $f_3 = 94\ GHz$

Magnetic Field $B_0 = 1.15$ T

Beam Voltage $V = 31\ KV$

Beam Current $I = 15.75\ Amp$

Pitch Angle $\alpha = 1.9$

Net Efficiency $\eta = 32.3\ \%$

Total Power Output $P_0 = 158\ kW$

Multi-frequency simulation of high gain fel oscillators

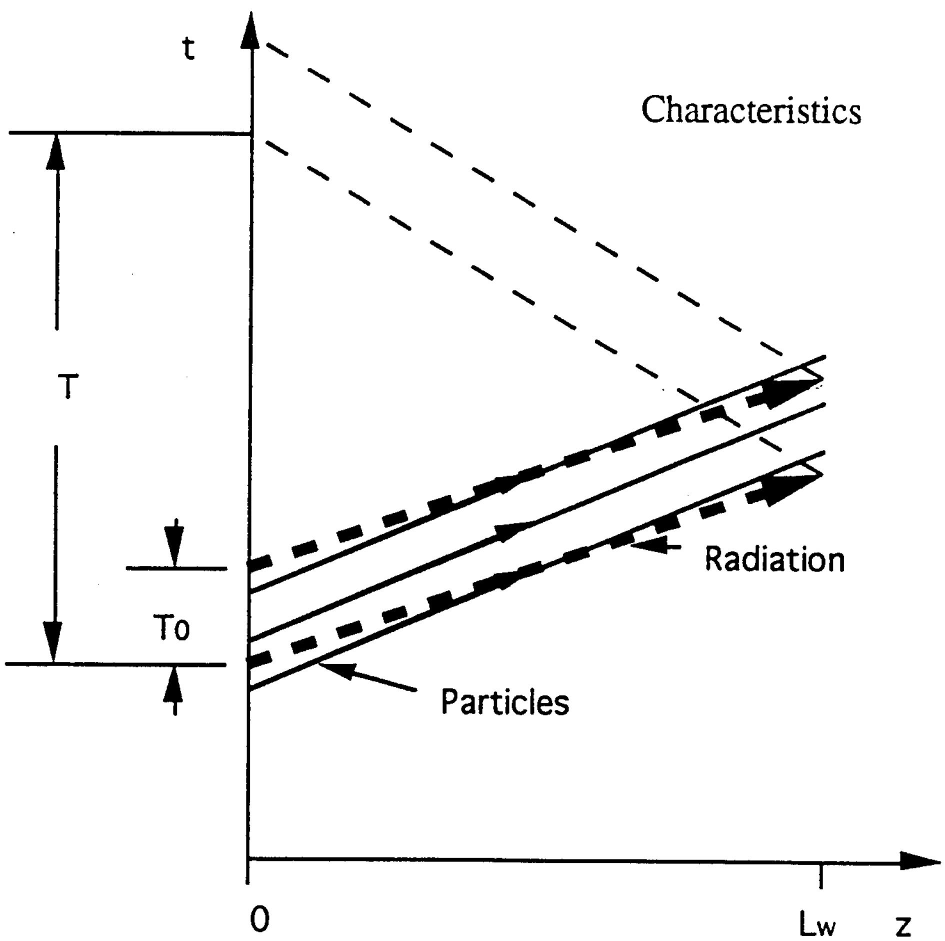
Radiation

$$\left[\frac{\partial}{\partial t} + v_g \frac{\partial}{\partial z}\right] \delta a(z,t) = -\frac{\pi I\, v_g v_w(z)\, \mathbf{e}_y \cdot \mathbf{e}_r^*\ C}{I_A\, k_0\, A_{eff}\, v_z} \langle \exp(-i\,\psi) \rangle$$

Electrons

$$\left[\frac{\partial}{\partial t} + v_z \frac{\partial}{\partial z}\right] \gamma = i\, \frac{k_0}{2}\, \delta a(z,t)\, v_w(z)\, \mathbf{e}_y \cdot \mathbf{e}_r\ C \exp(\,i\,\psi) + c.c.$$

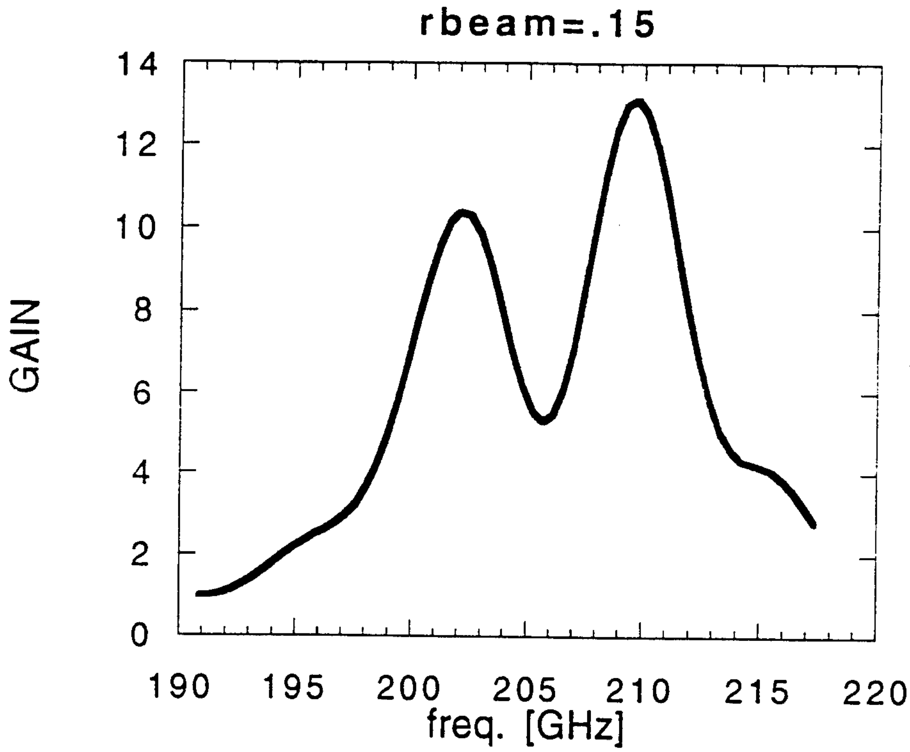
$$\left[\frac{\partial}{\partial t} + v_z \frac{\partial}{\partial z}\right] \psi = (\,k + k_w\,)\, v_z - \omega$$



Proposed FEM design

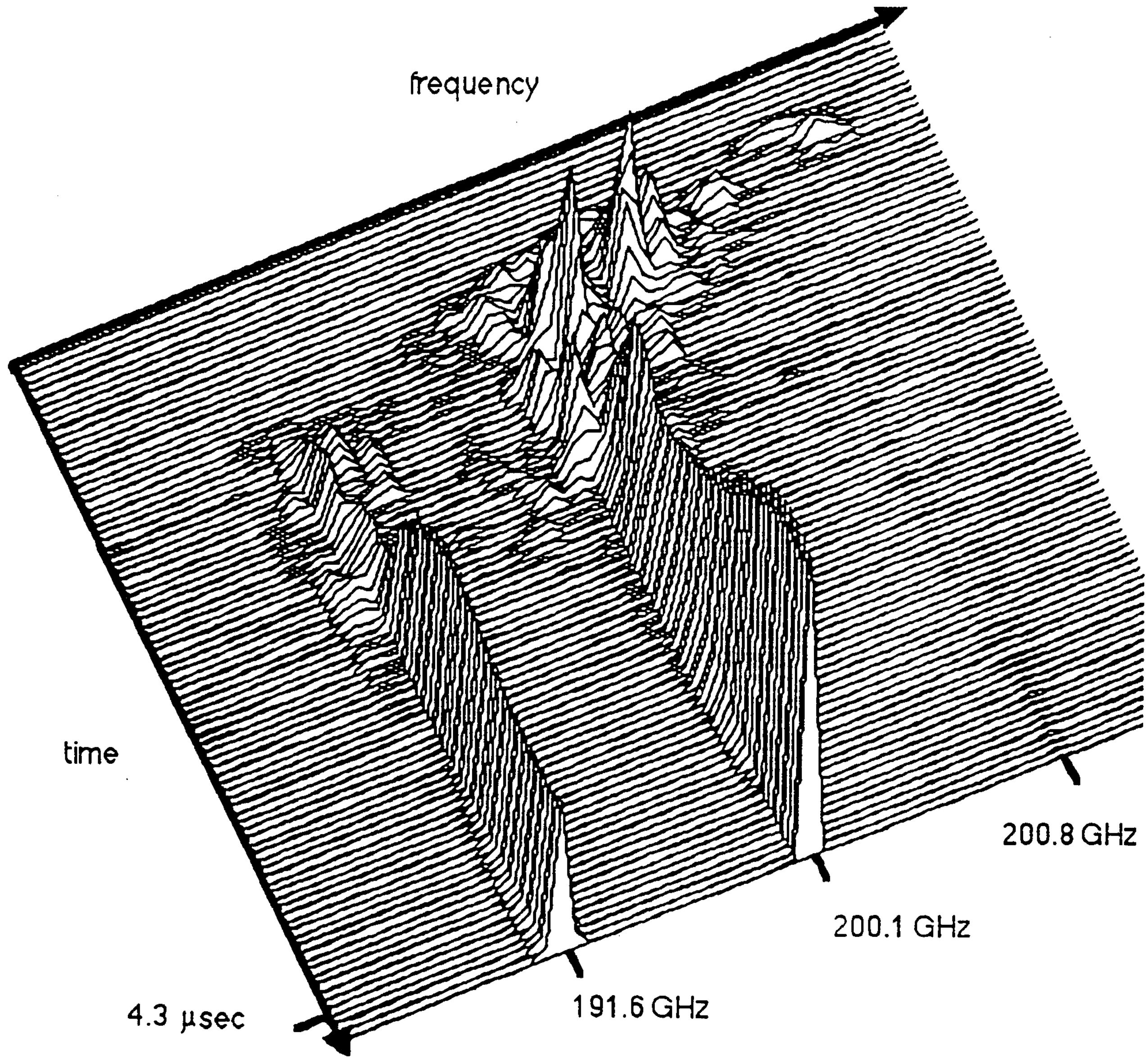
Beam voltage	1.75 MV
Beam current	12 A
Beam emittance	0
Beam radius	.15 cm
Wiggler period	4 cm
Peak field wiggler section 1	2 kG
Peak field wiggler section 2	1.7 kG
No. periods wiggler section 1	25 (23 full periods)
No. periods wiggler section 2	19 (17 full periods)
Inter wiggler gap	6 cm
Waveguide mode	HE_{11} rectangular
Waveguide width	1.5 cm
Waveguide height	2.0 cm
Cutoff frequency	12.49 GHz
Cavity length	382 cm
Power reflection coefficient	.21

Linear Gain



rbeam=.15
14
12
10
8
6
4
2
0
GAIN
190
195
200
205
210
215
220
freq. [GHz]

Output Spectrum versus Time



Modeling of harmonic gyroklystrons, phase locked gyro-oscillators, and gyro-twystrons

Recent Topics

1. **Theory of the relativistic gyrotwystron**

   input: cavity
   output: travelling wave amplifier

2. **Two harmonic prebunching of electrons in multi-cavity gyrodevices**

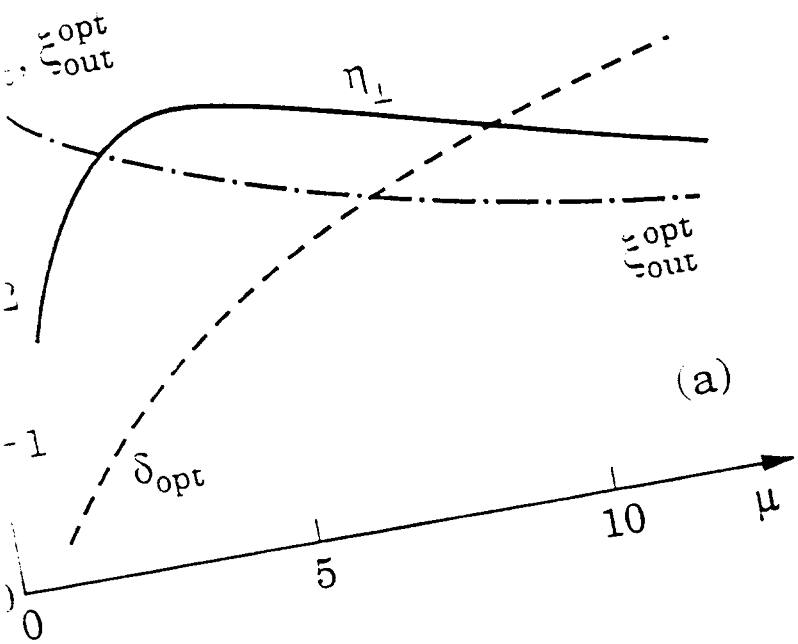
   input cavity: fundamental
   second cavity: fundamental/second harmonic
   output cavity: fundamental-fourth harmonic

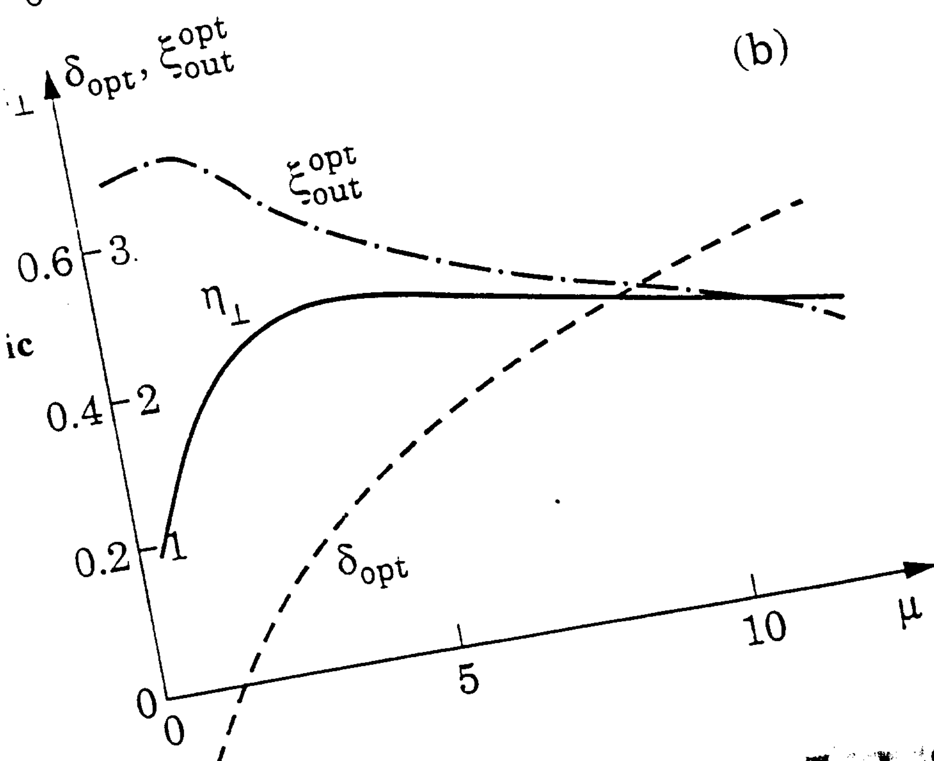
3. **Theory of phase-locked gyrotrons operating at cyclotron harmonics**

   input cavity: fundamental
   output cavity: second harmonic

relativistic gyrotwystron

ersus Output Cavity Length



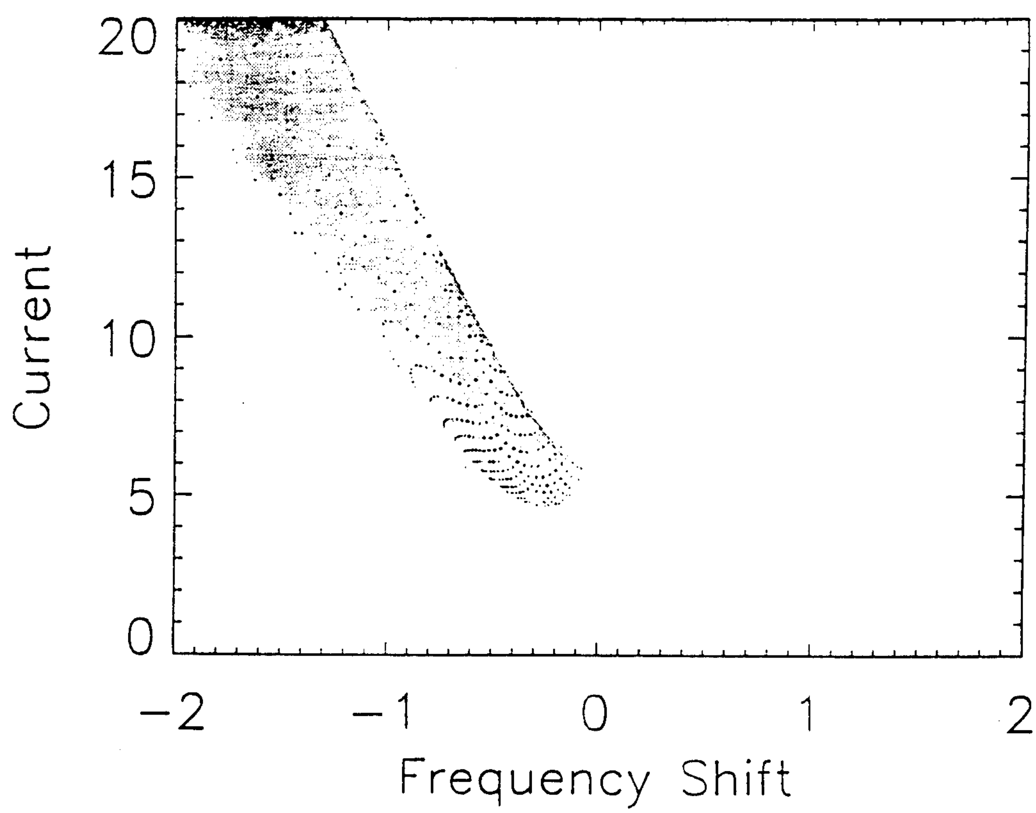


ic

3. Theory of phase-locked gyrotrons operating at cyclotron harmonics

Locking Bandwidth versus Beam Current

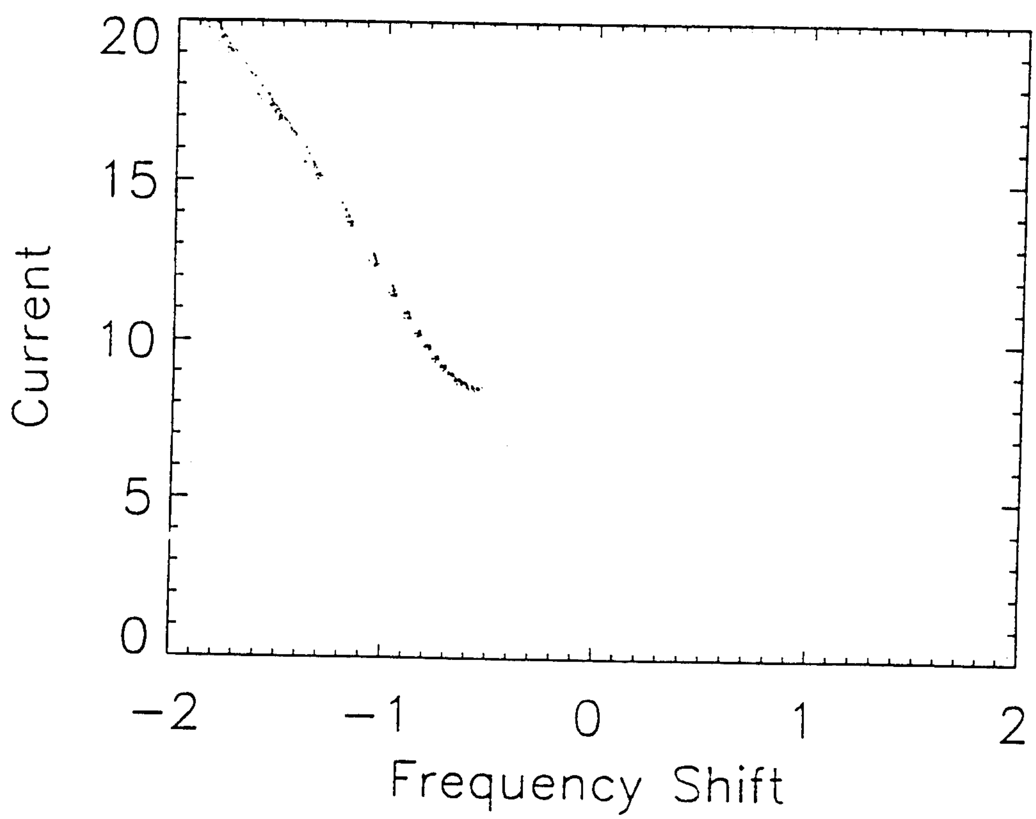
cold beam



3. Theory of phase-locked gyrotrons operating at cyclotron harmonics

Locking Bandwidth versus Beam Current

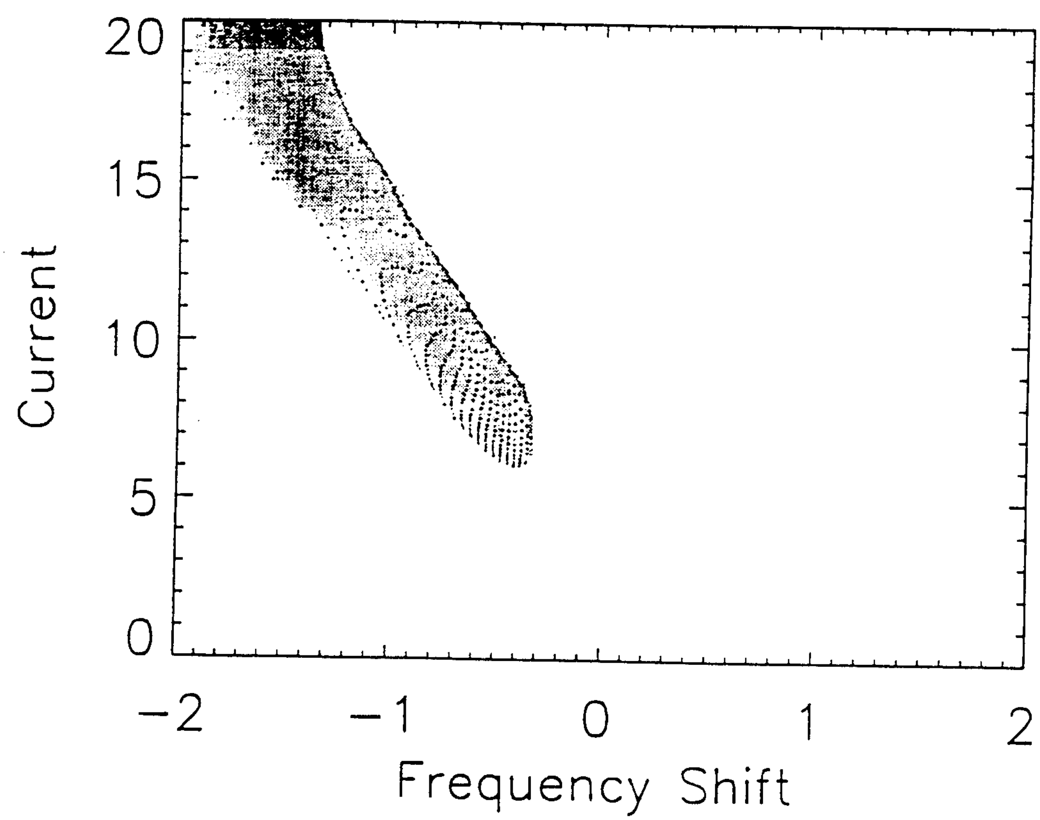
$\delta\alpha/\alpha$ = .2



3. Theory of phase-locked gyrotrons operating at cyclotron harmonics

Locking Bandwidth versus Beam Current

$\delta\alpha/\alpha$ = .2 with compensation



Current Efforts

Adapt individual models into a flexible simulation code for design and analysis of

- Phase-locked harmonic gyrotron oscillators
- Gyro-klystrons
- Gyro-twystrons
- Phigtrons

Included effects

- Frequency multiplication
- Multiple sections
- Backward waves

NUMERICAL SIMULATION
OF
SLOW WAVE DEVICES

MODELING OF

vacuum backward wave oscillators

plasma filled backward wave oscillators

EXAMPLES

homogeneous slow wave structure

effect of the finite pulse duration

cyclotron absorption effect

effect of the non-synchronous harmonic

effect of plasma

non-homogeneous slow wave structure

efficiency enhancement

THEORETICAL MODEL

- representation of the field

$$E(x,t)=\{\varepsilon_-(z,t)e^{i(k_- z-\omega t)}E_p(x,k_-)+\varepsilon_+(z,t)e^{i(k_+ z-\omega t)}E_p(x,k_+)\}+c.c$$

$$B(x,t)=\{\varepsilon_-(z,t)e^{i(k_- z-\omega t)}B_p(x,k_-)+\varepsilon_+(z,t)e^{i(k_+ z-\omega t)}B_p(x,k_+)\}+c.c$$

$\varepsilon_\pm(z,t)\rightarrow$ slowly varying envelope

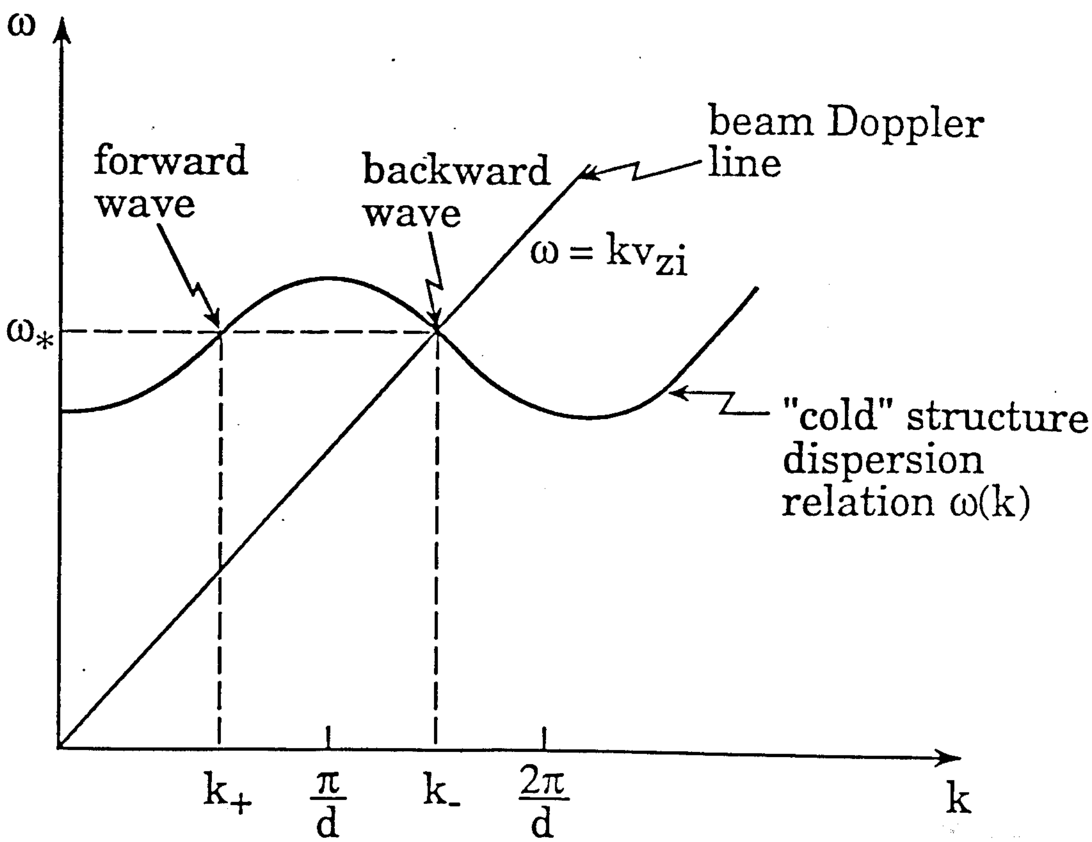
$$E_p(x,k_\pm)$$

periodic functions

$$B_p(x,k_\pm)$$

$$E_p(x,k_\pm)=\sum E_n(x_\perp,k_\pm)e^{ink_0 z}$$ $k_0 = \frac{2\pi}{d}$

$$B_p(x,k_\pm)=\sum B_n(x_\perp,k_\pm)e^{ink_0 z}$$



$$\frac{\partial \epsilon_-}{\partial t} + v_{g,-}\frac{\partial \epsilon_-}{\partial z} = -\int_0^d dz$$

$$\int_0^{2\pi/\omega} dt \int d^2\mathbf{x}_\perp \mathbf{E}_p^*(\mathbf{x}, k_-) \cdot \mathbf{j}e^{-i(k_- z - \omega t)}/U, \tag{9}$$

- electromagnetic energy per $|\varepsilon 2|$ contained in one period

$$U = \int_0^d dz \int d^2\mathbf{x}_\perp \frac{|\mathbf{E}_p|^2 + |\mathbf{B}_p|^2}{4\pi} \tag{10}$$

- group velocity for the vacuum backward electromagnetic wave

$$v_{g,-} = \int_0^d dz \int d^2\mathbf{x}_\perp \frac{c}{4\pi}\vec{z}_0 \cdot (\mathbf{E}_p(\mathbf{x}, k_-)$$

$$\times \mathbf{B}_p^*(\mathbf{x}, k_-))/U \tag{11}$$

- particle motion

$$\frac{dp}{dt} = q\left[E + \frac{\mathrm{v}}{\mathrm{c}} \times \left(B + B_{ext}\right)\right]$$

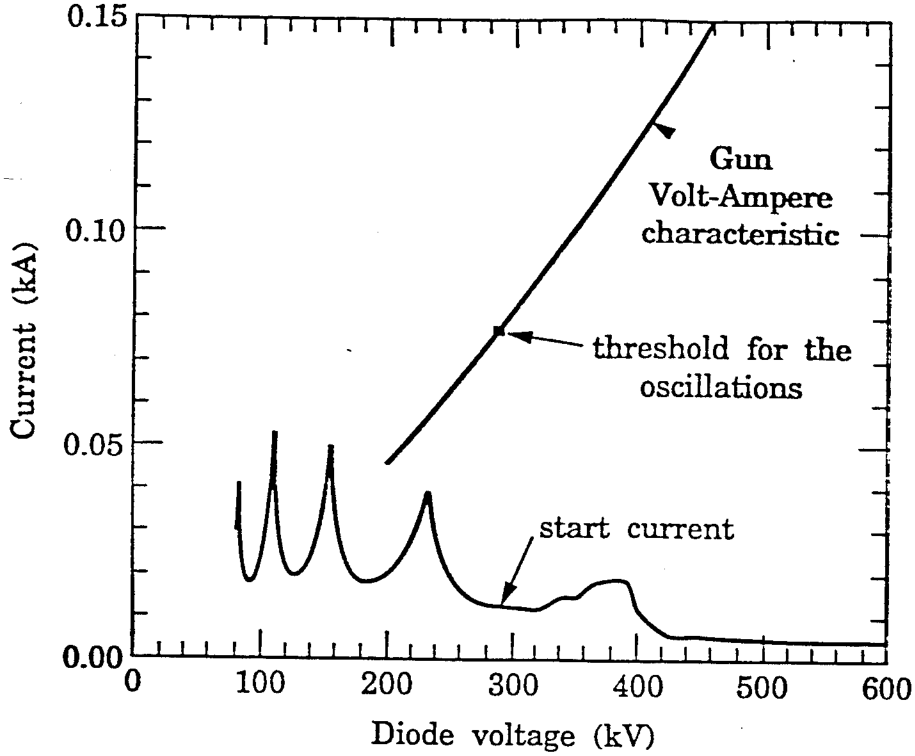
$$\frac{\mathrm{dx}}{dt} = \mathrm{v}$$

- assume that only two spatial harmonics of the backward wave can interact strongly with the beam

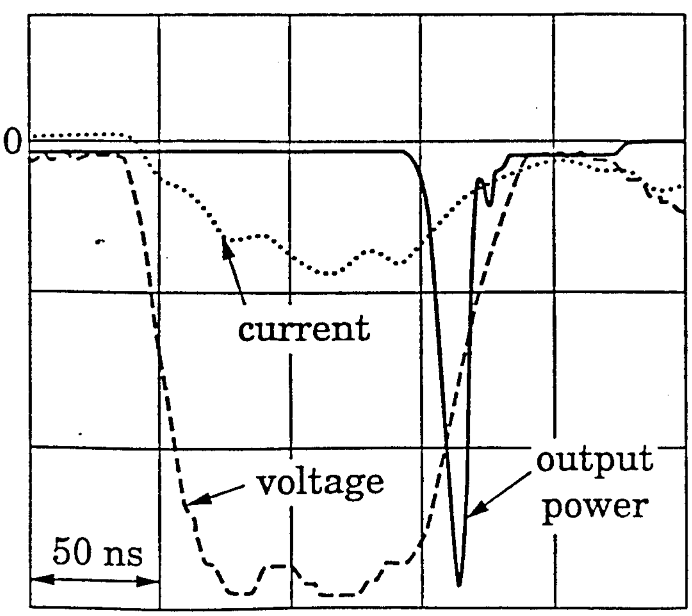
$$\mathrm{E}\,(x,t) = \varepsilon_{-}\, e^{i(k_{-} z - \omega t)} \left[a_0 E_0(x,k_{-}) + a_{-1} E_{-1}(x,k_{-})\, e^{-i(k_0 z)} \right] + c.c$$

$$\mathrm{B}\,(x,t) = \varepsilon_{-}\, e^{i(k_{-} z - \omega t)} \left[a_0 B_0(x,k_{-}) + a_{-1} B_{-1}(x,k_{-})\, e^{-i(k_0 z)} \right] + c.c$$

$d = 1.67$ cm
$L = 8d$
$r_{max} = 1.9$
$r_{min} = 1.1$



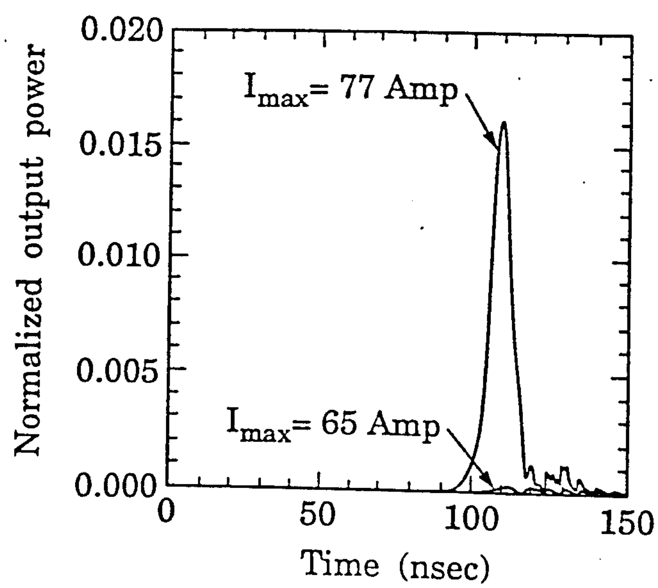
experiment

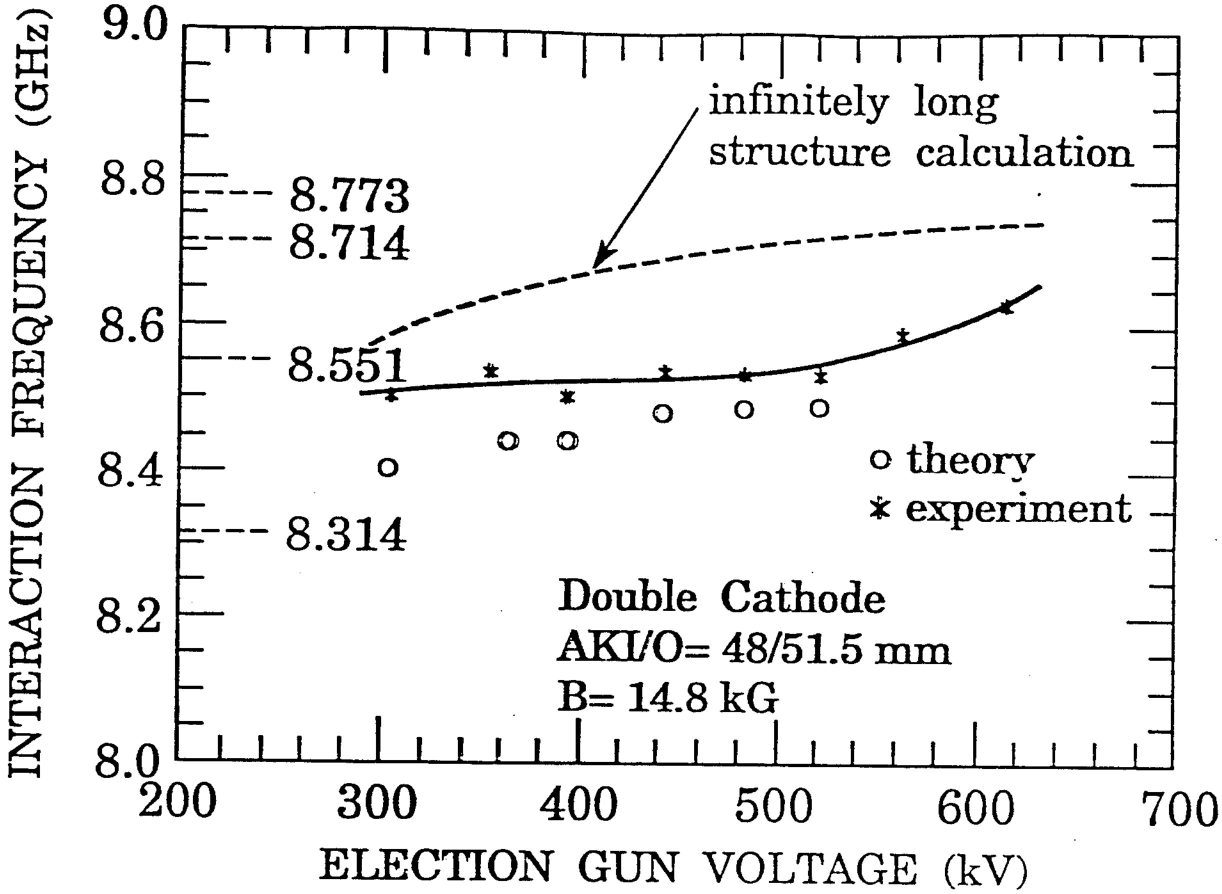


$V_{max} = 289$ kV

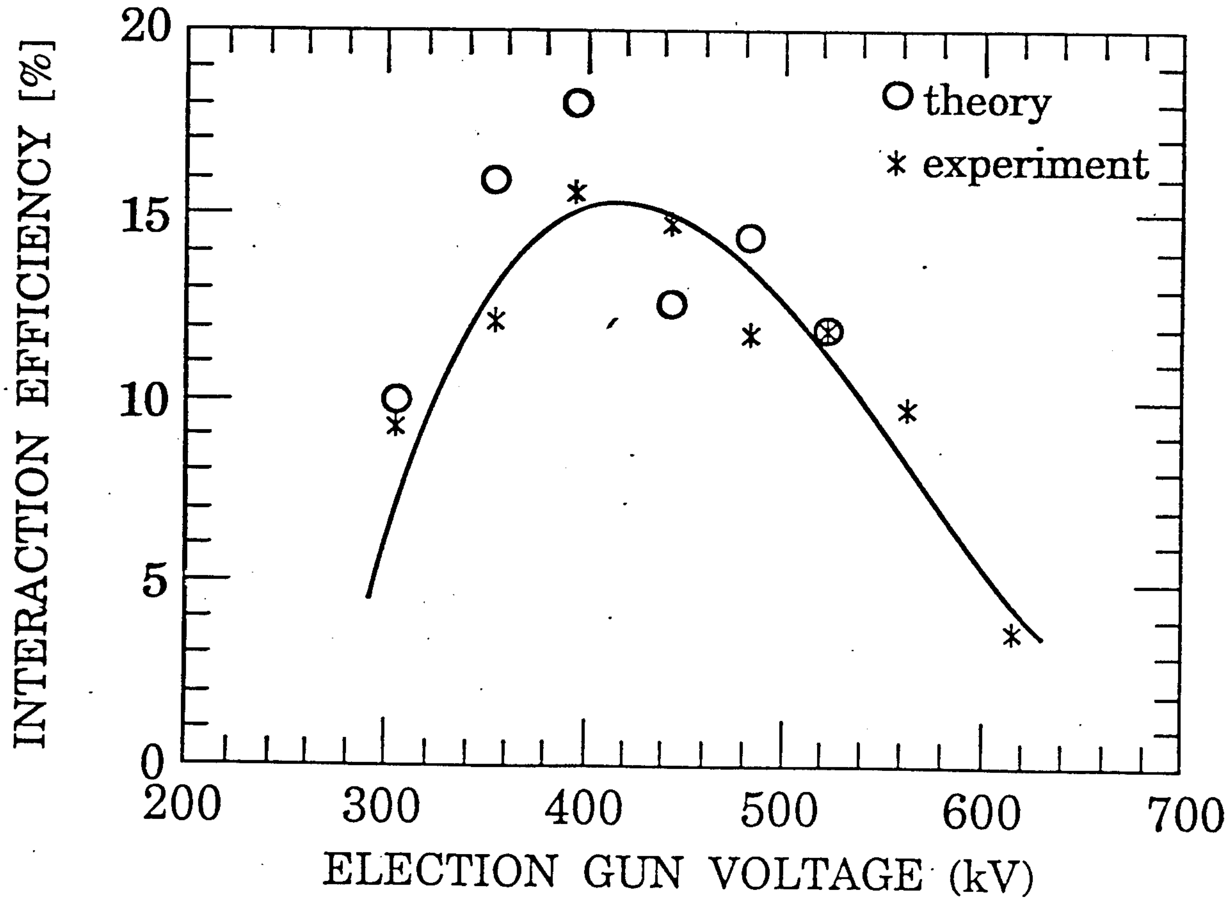
$I_{max} = 77$ A

theory




infinitely long
structure calculation
8.773
8.714
8.551
8.314
theory
experiment
Double Cathode
AKI/O= 48/51.5 mm
B= 14.8 kG
INTERACTION FREQUENCY (GHz)
ELECTION GUN VOLTAGE (kV)

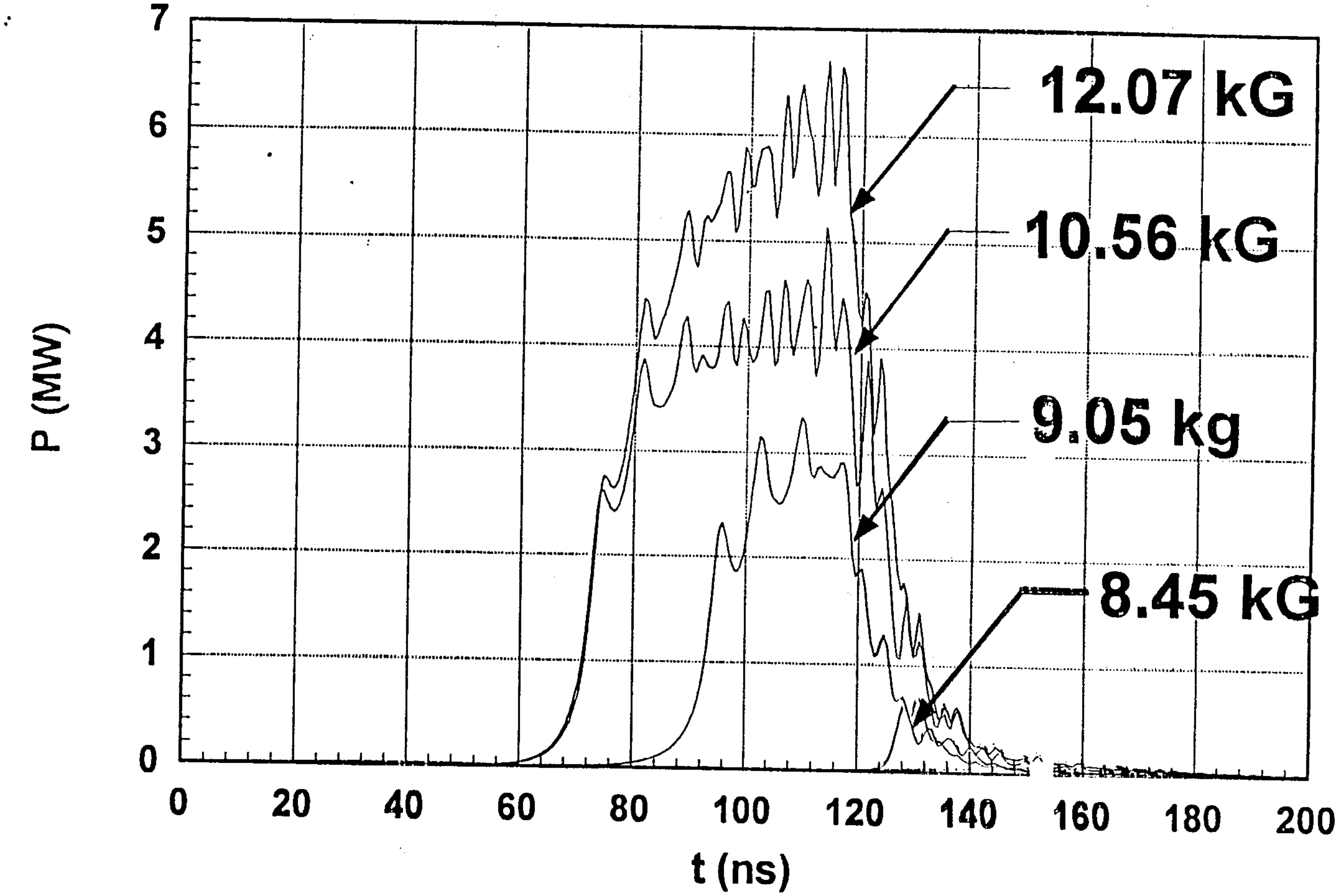
(a)


theory
experiment
INTERACTION EFFICIENCY [%]
ELECTION GUN VOLTAGE (kV)

(b)

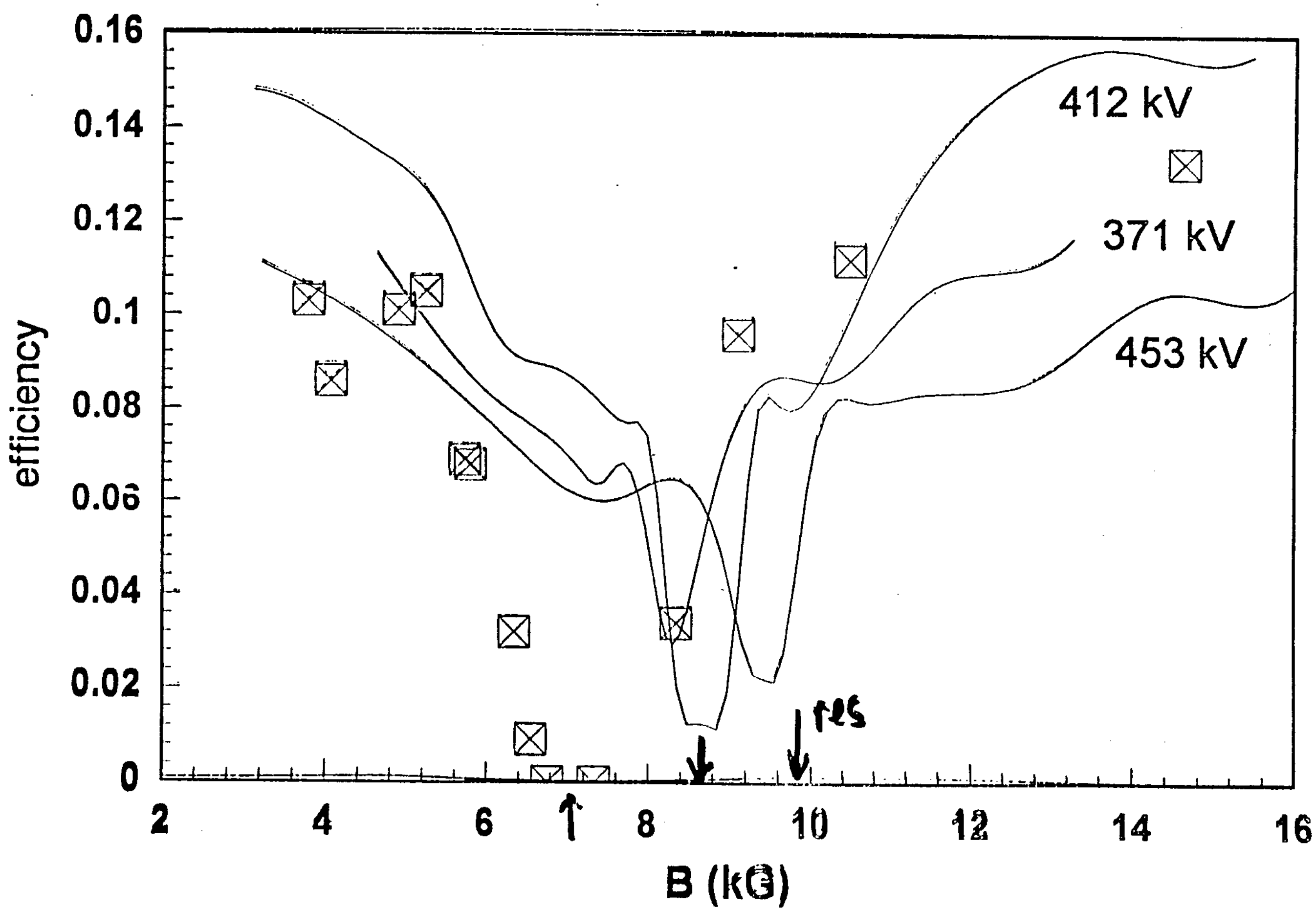
$I = 110\ A$
$V = 412\ kV$

Cyclotron Absorption Effect



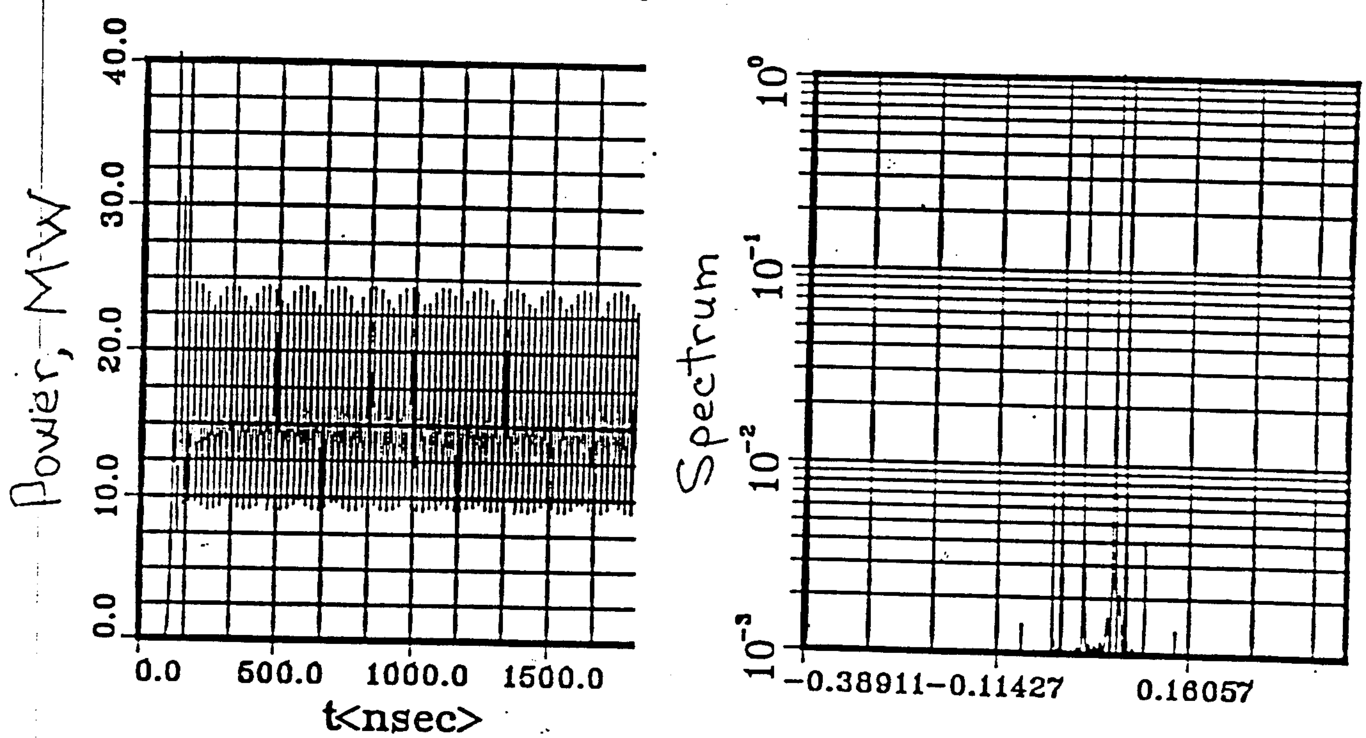
$B_{res} \simeq 9.6\ kG$
$B_{sim} \simeq 8.5\ kG$
$B_{exp} = 7.3 \pm 0.3$

Cyclotron Absorption Effect

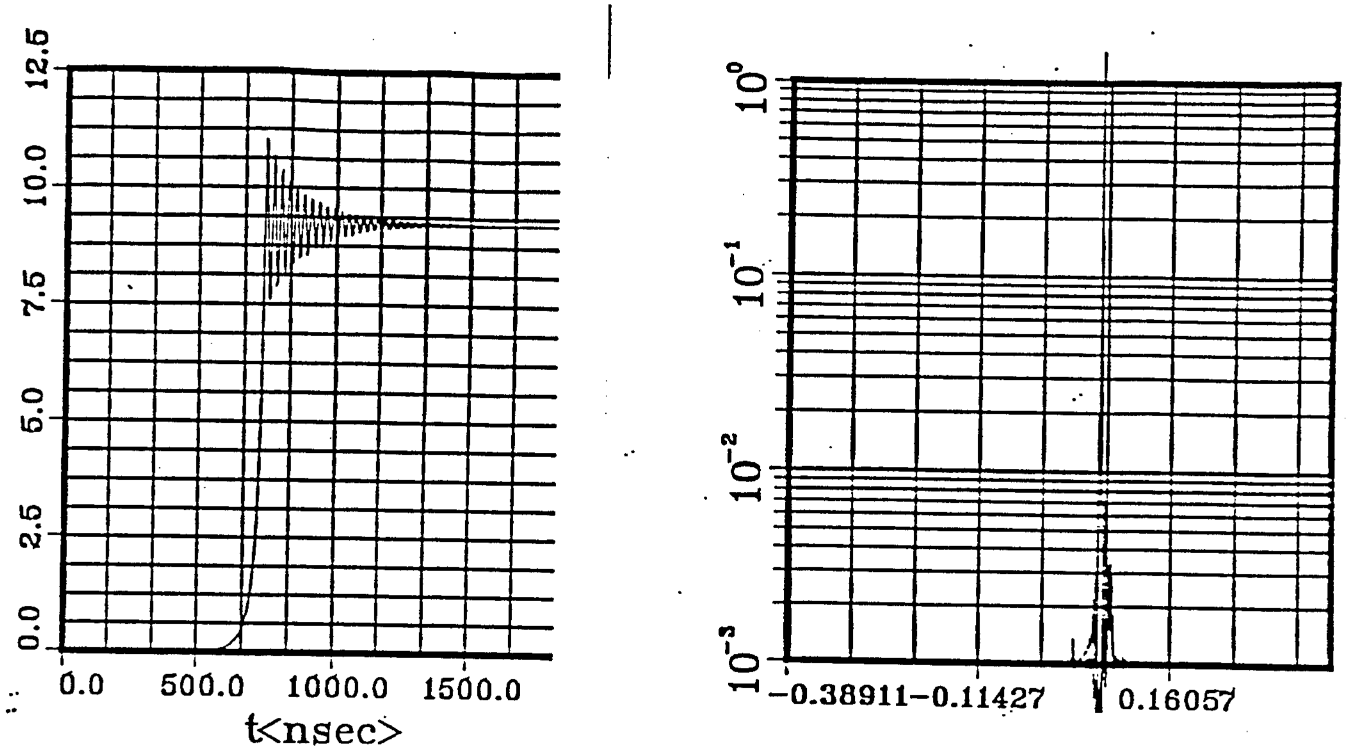


$$B_{res} = \frac{mc}{q}\frac{2\pi}{d}(\gamma\beta)$$

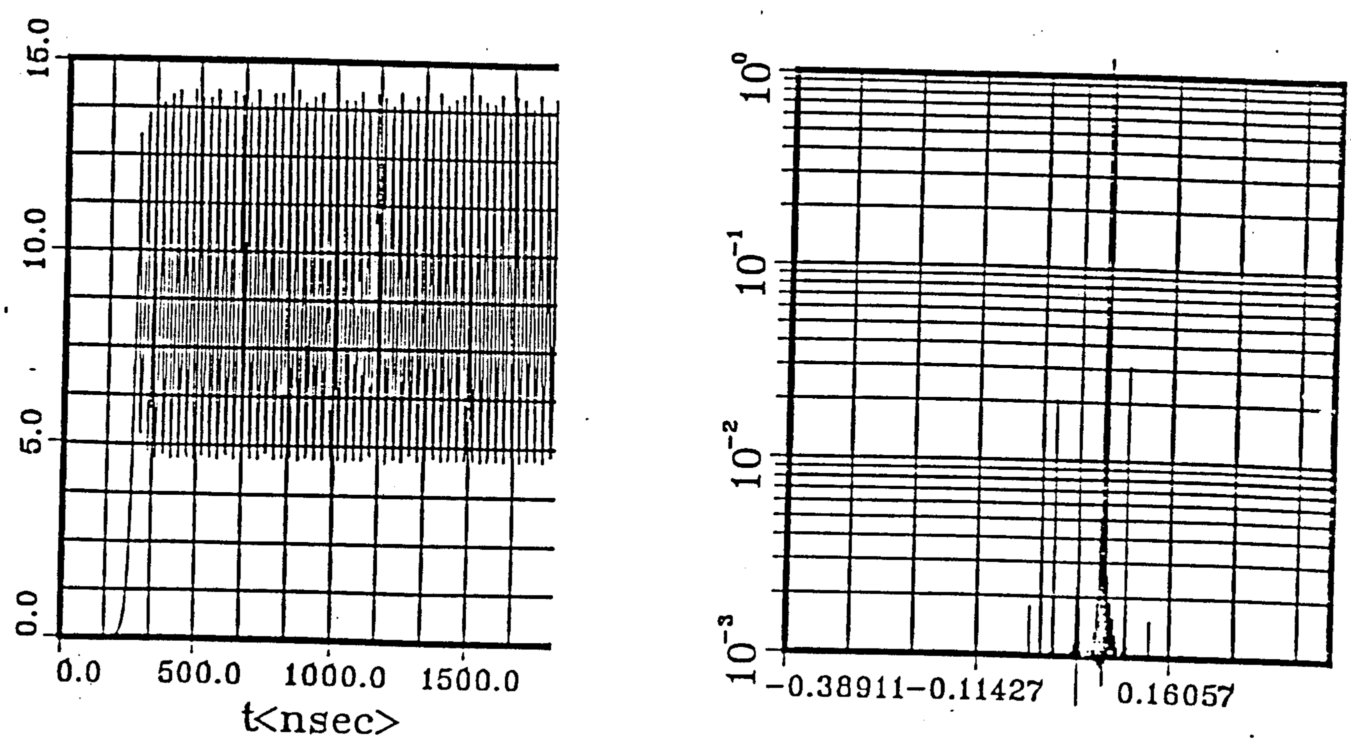
Only the synchronous harmonic



$\psi = 0$



$\psi = \frac{\pi}{16}$



Modeling of plasma filled Backward Wave Oscillator

Ph. D. Thesis

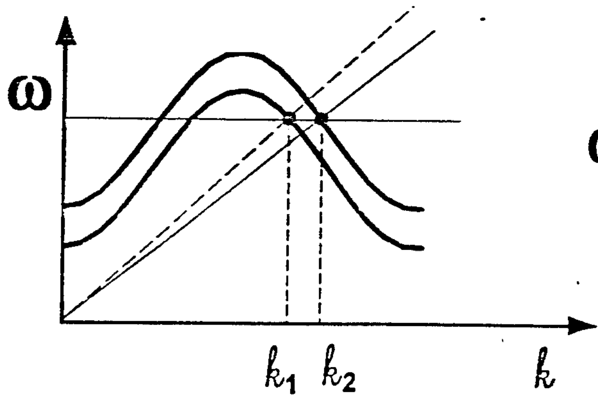
Susan Miller

Efficiency enhancement of relativisitc backward wave oscillator

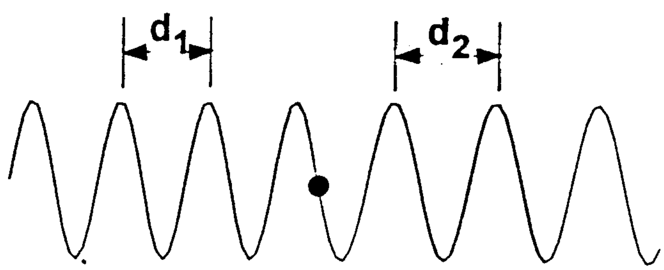
- vary coupling impedence along the interaction region

- sudden increase in phase velocity of the synchronous wave.

Efficiency enhancement of high power relativistic backward wave oscillator



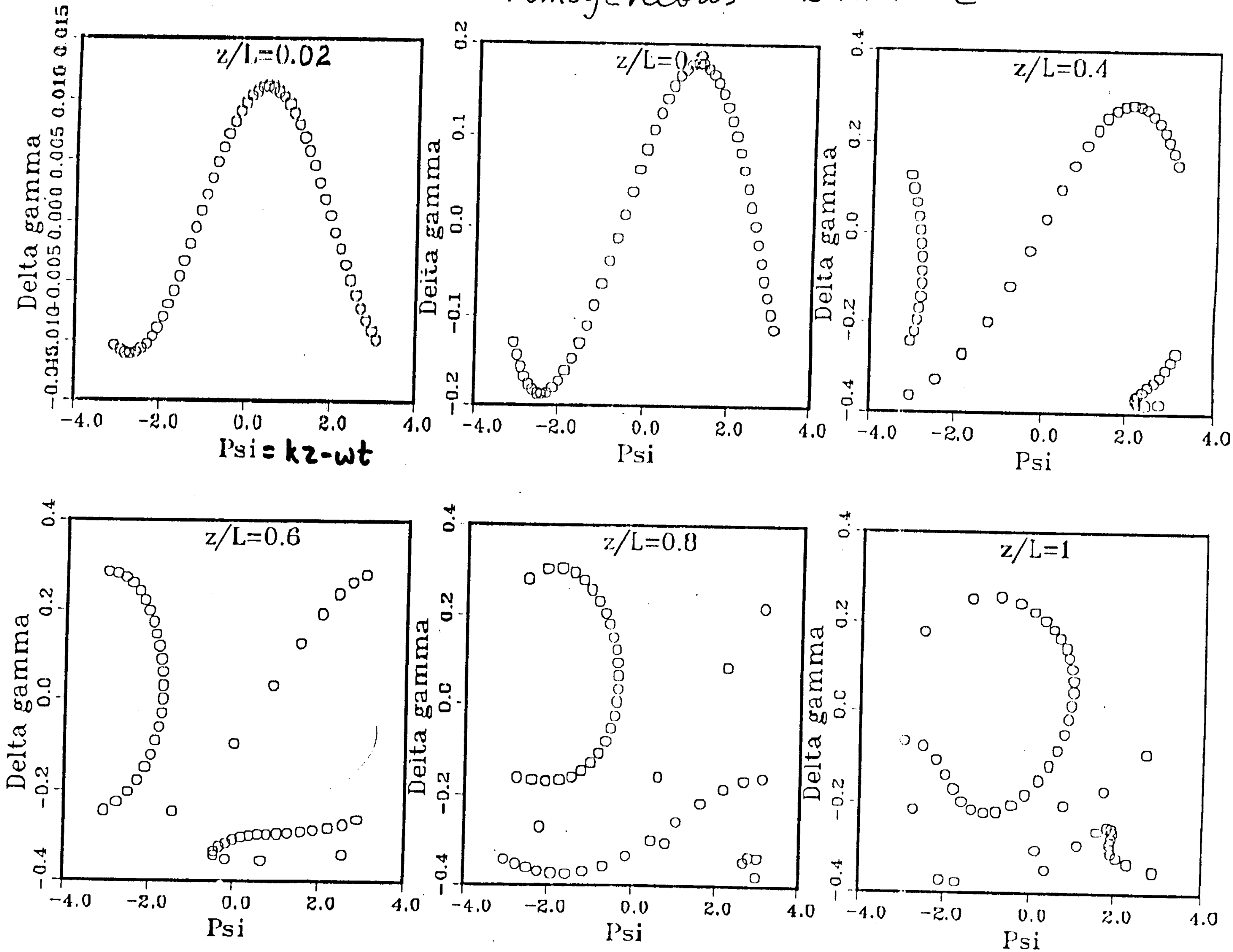
$\omega = k\, v_z$

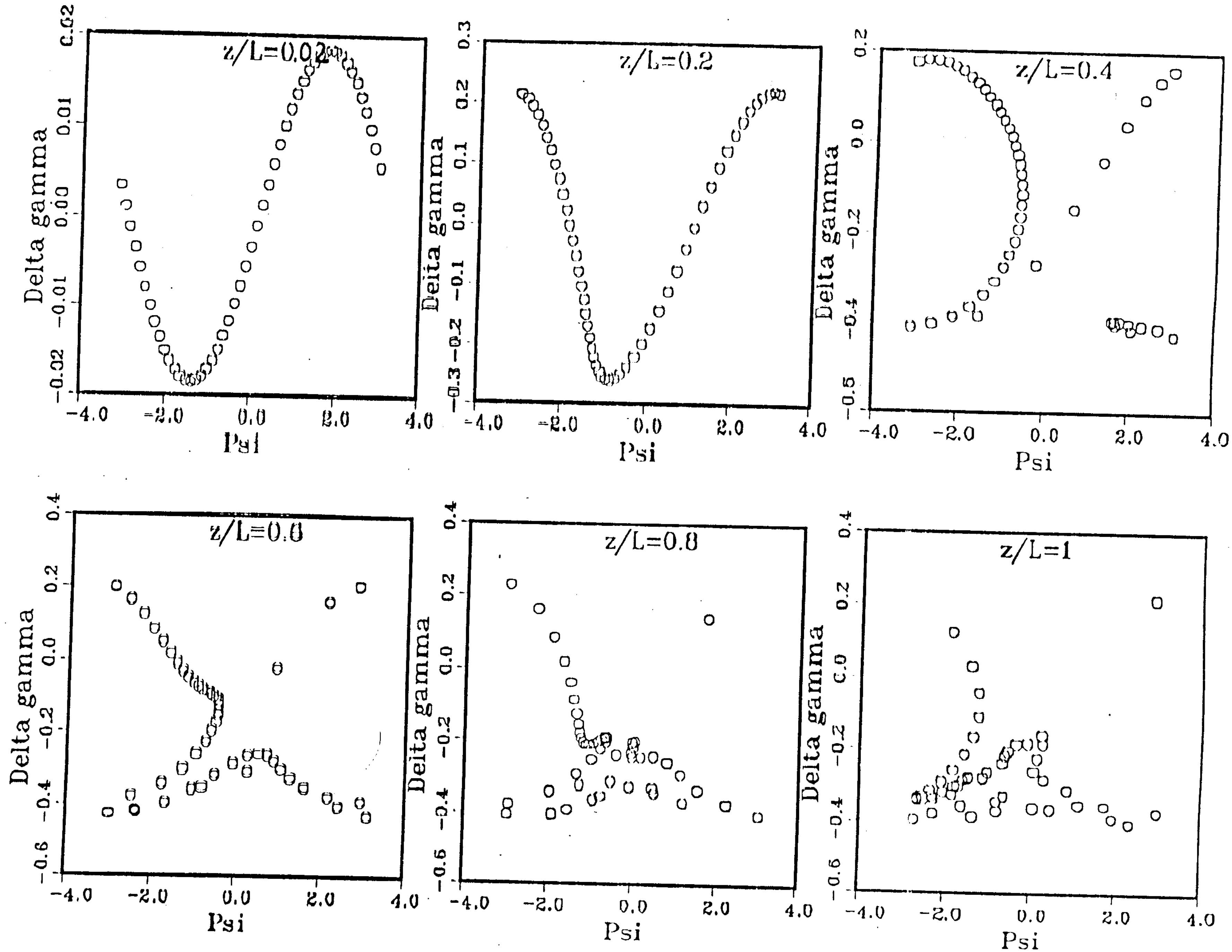


$d_2 > d_1$

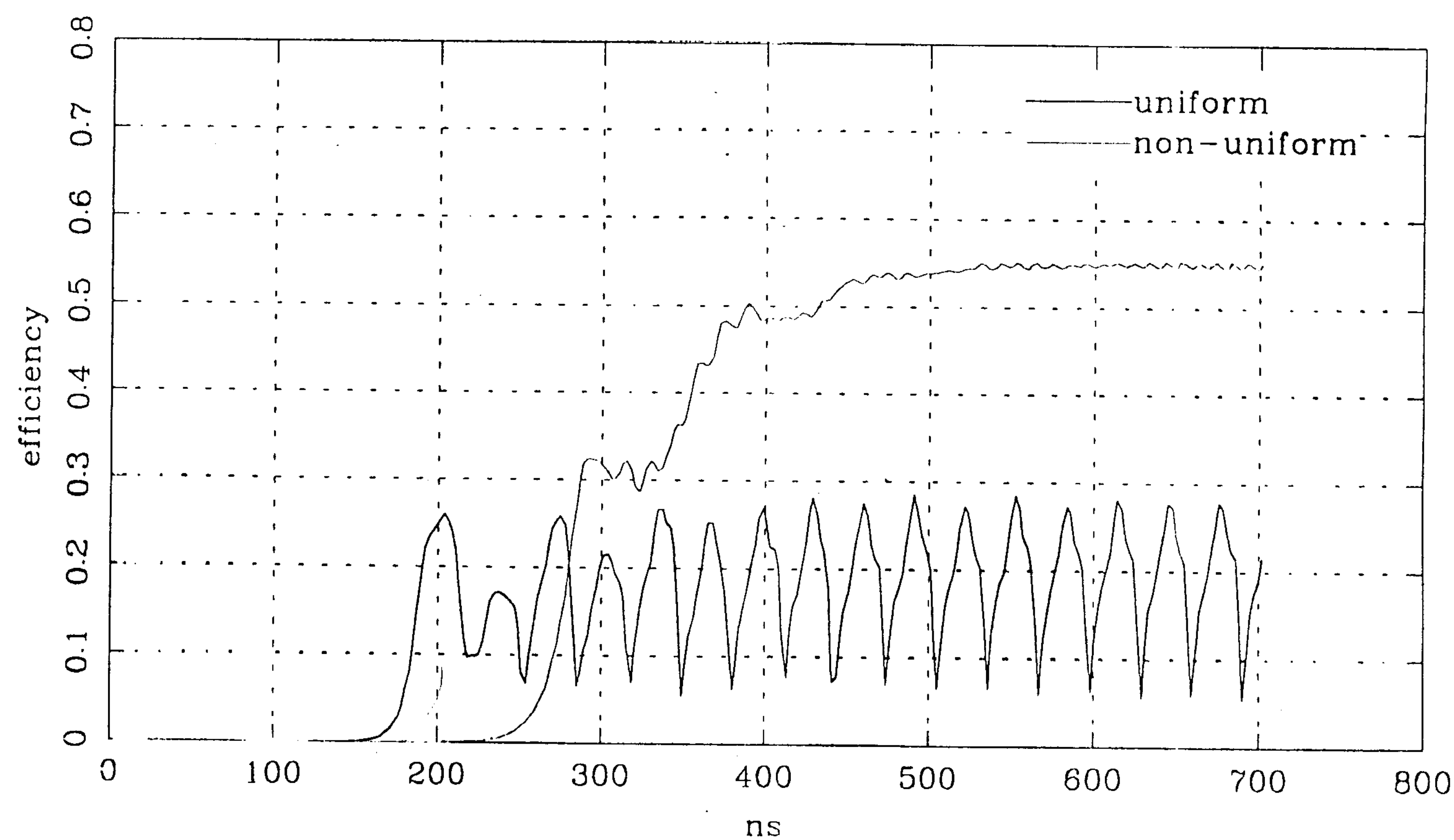
Homogeneous structure

$(\gamma(z)-\gamma_i)/\gamma_i$

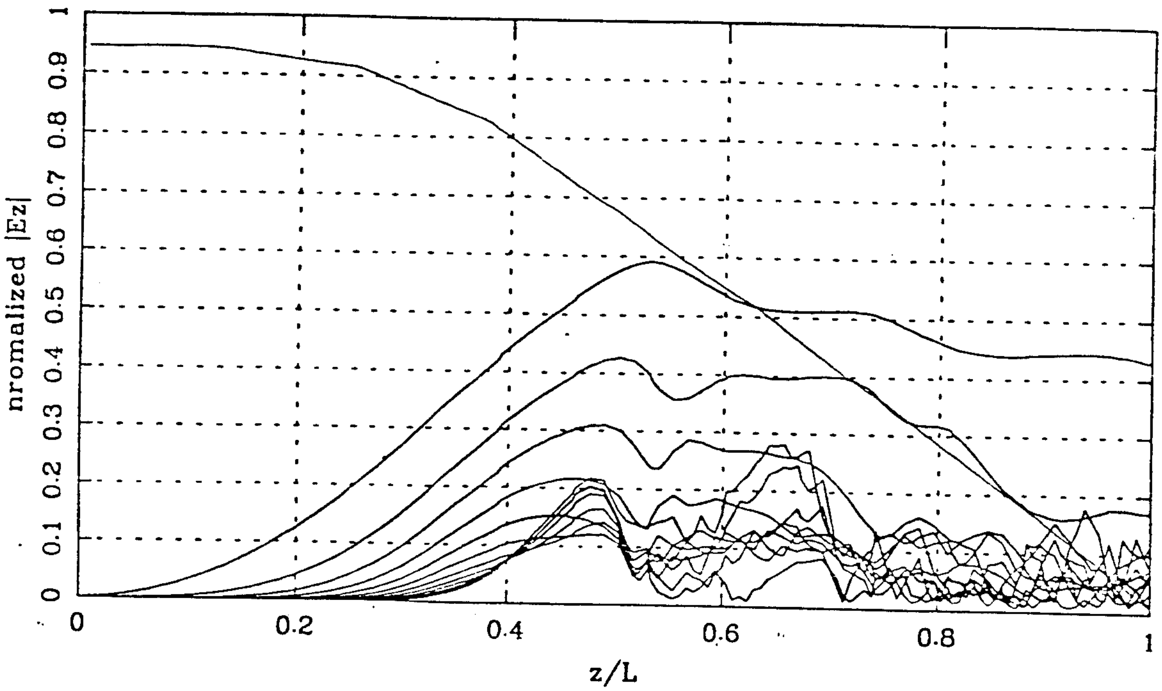



z/L=0.02
z/L=0.2
z/L=0.4
z/L=0.6
z/L=0.8
z/L=1
Delta gamma
Psi
-4.0
-2.0
0.0
2.0
4.0

Efficiency vs. time (500 keV & 100 A beam)
with space charge neglected for uniform
and non-uniform structures



Amplitude of synchronus field (red) and
space charge harmonics fields (black)
vs. axial distance
(500 keV & 5 kA uniform sturcture)

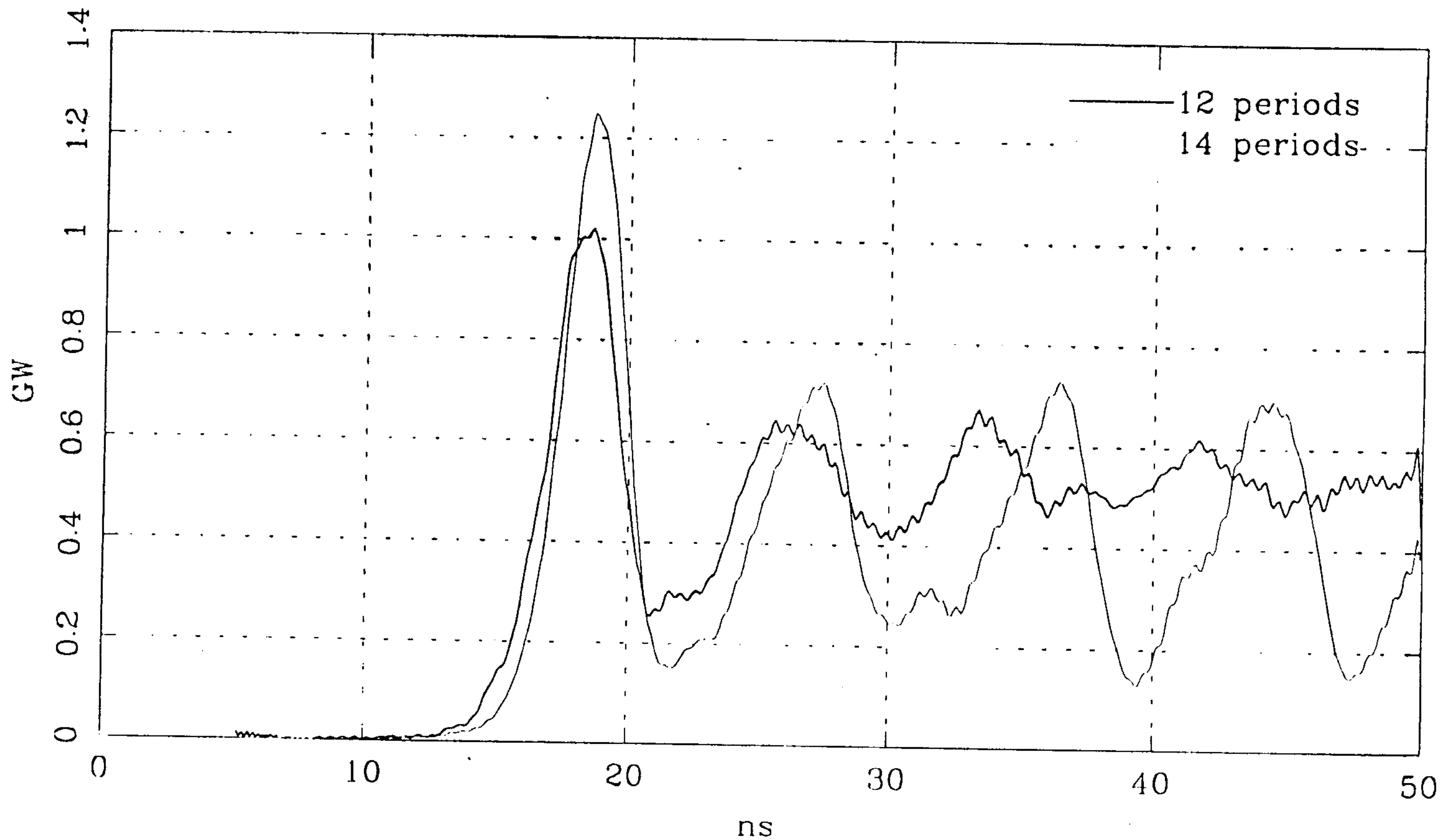


$$\frac{\partial\gamma}{\partial z} = \text{"radiation term"} - \frac{8I}{I_A\, k_0\, r_b^2}\,\mathrm{Re}\{\sum_{n=1}^{N} R_n\, e^{i\, n\psi} \langle e^{-i\, n\psi}\rangle\}\,,$$

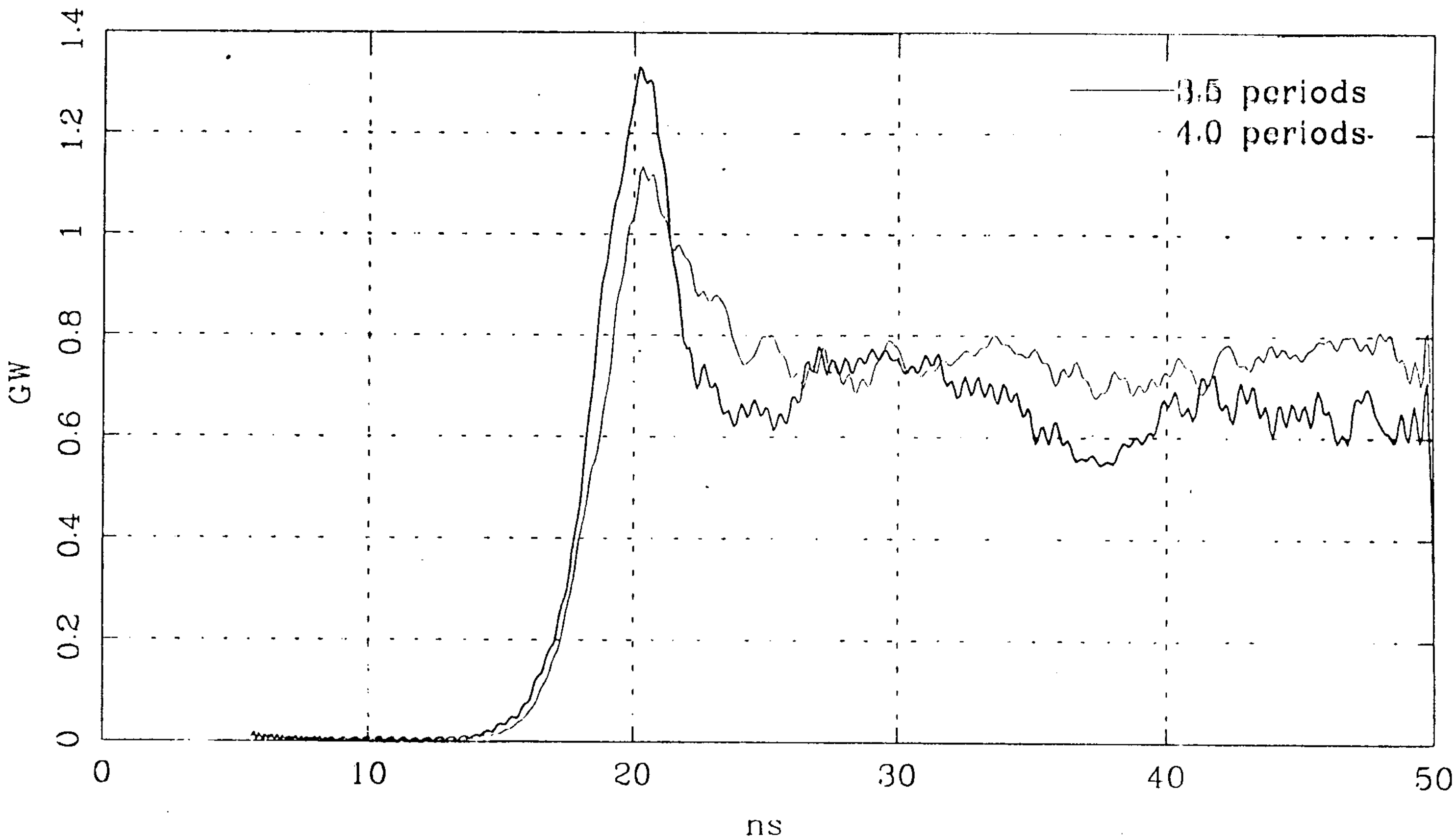
particle phase: $\psi = k_{-}z - \omega t$

R_n = geometric space charge reduction factor

MAGIC simulation of S--band BWO
with uniform structure
(12 and 14 periods long)
Output power vs. time



MAGIC simulation of S-band BWO
with non-uniform structure
(transition at 3.5 and 4.0 periods)
Output power vs. time



Current efforts

PIC modeling of non-homogenous structures

modeling of plasma filled backward wave oscillator

Possible new efforts

adopting our models to simulate multi-frequency phenomenon in slow wave devices such as TWT's

1. self-excitation of spurious oscillations
2. simultaneous amplification of a number of signals at different frequencies