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The electron dynamics in a relativistic klystron scheme was investigated using the same code MAGIC. The bunching of the injected electron beam was achieved by periodic deflection of the electron beam and subsequent deflection by 270 degrees in a static magnetic field. The simulation achieved oscillation of the system with a single-cell cavity.

A single-cell cavity resonator was constructed and investigated experimentally. It achieved a quali factor of Q = 7800 after silver brazing the parts.

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FINAL TECHNICAL REPORT

(01 July 1992 until 31 July 1996)

Title: **"Investigation of Charged Particle Dynamics in Electromagnetic Fields."**

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Grant Number: **AFOSR Grant #F49620-92-J-0348**

Abstract:

Photon interaction with plasma turbulence induced by relativistic beam-plasma instability was studied by the 2 and 1/2 D particle simulation code MAGIC. The relativistic beam induced the instability through coupling between the beam-plasma mode and an electromagnetic mode resulting in electromagnetic turbulence. The observed growth rate of the instability, as a function of beam velocity and wave vector, agreed well with the linear theory. Harmonic generation is observed in the simulation at the second harmonic. Harmonic generation falls off for frequencies above the electron plasma frequency. Harmonic generation falls of for a relativistic factor of the beam above 3.

The electron dynamics in a relativistic klystron scheme was investigated using the same code MAGIC. The bunching of the injected electron beam was achieved by periodic deflection of the electron beam and subsequent deflection by 270 degrees in a static magnetic field. The simulation achieved oscillation of the system with a single-cell cavity.

A single-cell cavity resonator was constructed and investigated experimentally. It achieved a quality factor of $Q = 7800$ after silver brazing the parts.

The Investigation of Charged Particle Dynamics in Electromagnetic Fields consists of two main parts.

Part I consists of an investigation of the relativistic electron beam -plasma instability and its interaction with electromagnetic waves.

Part II consists of an investigation of a deflecting relativistic klystron.

Part I: Relativistic Electron Beam-Plasma Instability and Interaction with Electromagnetic Waves.

Research assistants: John Masten

Supervisor: Dr. Osamu Ishihara

1.1 Introduction

The subject of this report is the investigation of the electromagnetic relativistic beam-plasma instability and generation of electromagnetic radiation at $\omega = 2\omega_p$ resulting from plasma interaction with injected electromagnetic radiation at $\omega = \omega_p$. The dispersion relation for the relativistic beam-plasma instability is solved numerically as a function of both beam velocity and wavenumber. MAGIC (MAGnetic Insulation Code) is a particle code, used here to simulate the relativistic beam-plasma instability, the electromagnetic growth rates are compared to theory and good agreement is found. Electromagnetic radiation is injected into the plasma at $\omega = \omega_p$, radiation at $\omega = 2\omega_p$ is observed. Radiation intensity is found to depend on incident radiation intensity and beam velocity.

1.2 Growth Rate Comparison Between MAGIC Simulation and Numerical Solution of Dispersion Relation

The linear dispersion relation for the relativistic beam-plasma instability was solved numerically for the growth rate of the electromagnetic mode as a function of both beam velocity and wavenumber, for the case $k_\perp = k_z = \frac{\omega_p}{v_{bo}}$. The numerical results were compared to MAGIC simulations. The temperature of the modeled plasma is on the order of $5keV$ and varies depending on the instability wavenumber mode being investigated. The density and temperature of the modeled plasma were chosen to lie within ranges corresponding to fusion plasmas, in order to allow comparisons with fusion plasma instabilities. Based on the values of temperature and density the number of macroparticles and number of grid spacings were chosen to satisfy memory and reasonable computational time constraints. The maximum electrostatic growth rate gives rise to a dominant mode corresponding to $k_z = \frac{\omega_p}{v_{bo}}$, which varies from 222.14 to 209.5 for beam Lorentz factors of 3 to 40, and couples into the electromagnetic mode. The plasma size was chosen such that the dominant mode would satisfy the boundary conditions. The grid spacing was chosen such that the dimensions of the plasma correspond to $z = \frac{2\pi}{k_z}$ and $x = \frac{2\pi}{k_\perp}$, where z and x are the dimensions in the longitudinal and transverse directions and $k_\perp$ has been set equal to k_z. The plasma consists of immobile ions (4.9×10^6 proton masses) and thermal electrons with a vacuum above and below. The simulation consists of symmetry boundaries in the direction of the beam at z=0 and $z = L_z$ (L_z is the length of the simulation in the z direction) and absorbing boundaries perpendicular to the beam at $x = 0$ and $x = L_x$ (L_x is the length of the simulation in the x direction). The beam-plasma instability was studied for $\gamma_o = 3 - 40$ and the growth rates versus beam velocity and wavenumber were calculated. Figure 1 shows the comparison of the growth rate solved numerically to the linear growth rate found from the MAGIC simulation. The linear growth rate from the MAGIC simulation was calculated by finding the slope of the electromagnetic field energy on a semi-log plot. There is a good agreement between the numerical solution and the MAGIC simulation, both exhibit the same trend. Figure 2 is a plot of growth rate versus wavenumber for the numerical solution and the MAGIC simulation, where $k_\perp = k_z = \omega_p / v_{bo}$. The numerical solution and the MAGIC simulation show the same trend. Although the agreement is not as good as seen in Figure 1, the numerical solution shows zero growth rate as k_z goes to zero and a cutoff at $k_z = 235 rad/m$, with a peak growth rate at $k_z = 210 rad/m$. The MAGIC simulation shows a decreasing growth rate for small k_z and a cutoff at $k_z = 340 rad/m$ with a peak at $k_z = 230 rad/m$. The peak at certain k_z value and overall spread in the growth rate found in the MAGIC simulation can be attributed to coupling between more than one wavenumber mode in the plasma. In collecting the data for Figure 1, the boundary conditions can be used to isolate the dominant mode which would quickly outgrow the other modes allowing close agreement with theory. It should be noted that the growth rate for Figure 2 is a function of the wavenumber and not of the dominant mode of growth. Thus, two modes with similar growth rates would grow together and couple into other modes, resulting in a larger discrepancy between theory and simulation.

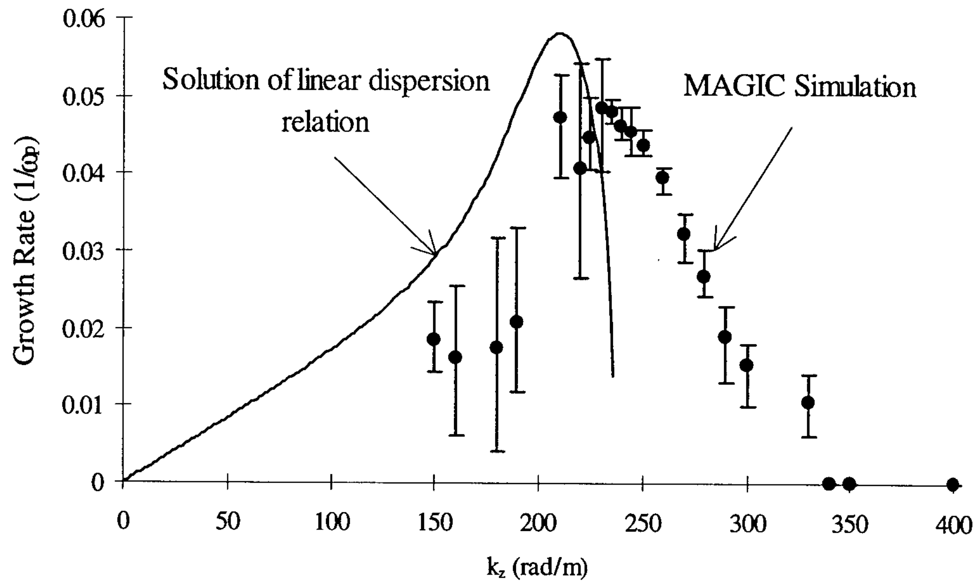

Figure 2 Growth rate (scaled by ω_p) from numerical solution of dispersion relation and MAGIC simulation vs. wavenumber.

MAGIC correctly simulates the electromagnetic behavior of the beam-plasma instability, in the form of plateauing of distribution function, trapping of the beam electrons, heating of the plasma, and growth rate of the electromagnetic field. MAGIC predicts an increase in magnetic field energy, generated as a result of the electromagnetic instability, as the beam velocity becomes more relativistic.

1.3 Electromagnetic Wave Plasma Interaction

The beam-plasma instability is used to generate electromagnetic turbulence in the plasma. Once the instability has saturated an electromagnetic wave of frequency $\omega = \omega_p = 6.28 \times 10^{10}\, rad/s$ is injected into the plasma. The interaction of the incident transverse electromagnetic wave and the plasma is studied through the use of the frequency spectrum of the plasma fields. The interaction is studied for varying beam velocities and incident wave intensities. After the beam-plasma instability has saturated, at

$t = 3ns$, the incident wave is injected and the simulation is run until $t = 8ns$. The incident wave is injected along the absorbing boundary at $x = 0$ with $\mathbf{k}$ in the x direction transverse to the beam direction. The electric field of the incident wave is polarized in the z direction. The incident wave propagates through the vacuum region and penetrates the plasma.

Figures 3 and 4 show the plasma field energy spectrum in a plasma subjected to the beam-plasma instability. An incident wave is injected into the plasma with a frequency of $\omega = \omega_p$ with an electric field strength of $1.25 \times 10^6 V/m$. The beam-plasma instability causes a variation in the plasma density which will result in a scattered wave at $\omega = 2\omega_p$. The incident wave component as well as a field component at $\omega = 2\omega_p$ can be seen in Figures 3 and 4.

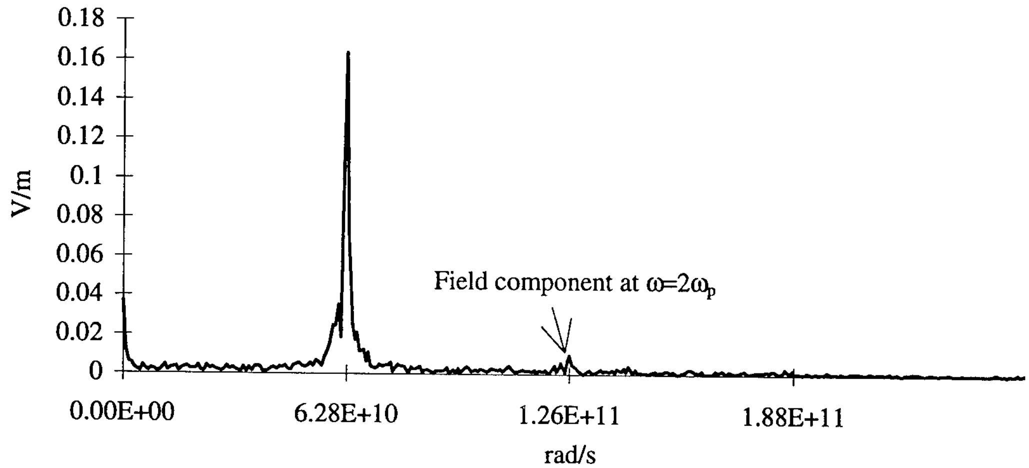

Figure 3 Plasma field spectrum for longitudinal E field, γ_o=20 and incident wave E field strength of 1.25×10^6 V/m.

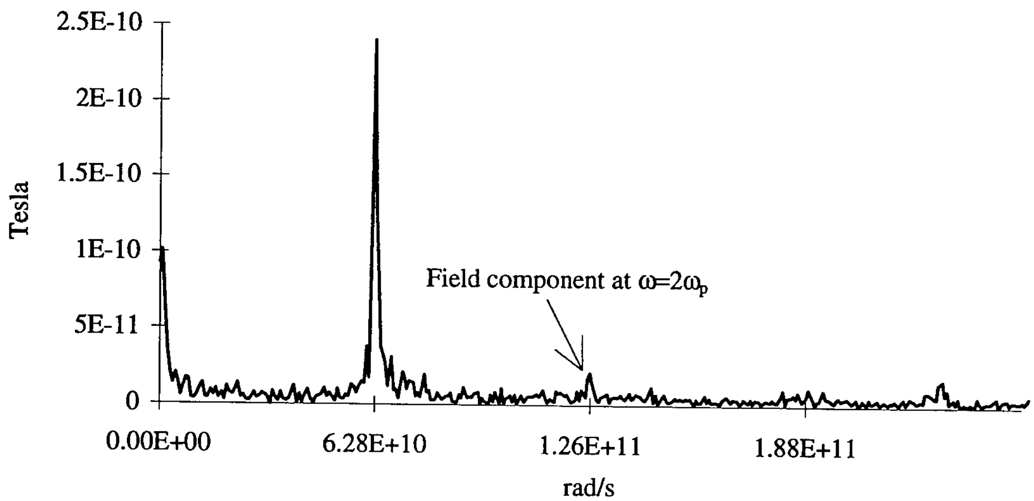

Figure 4 Plasma field spectrum for transverse B field, γ_o=20 and incident wave E field strength of 1.25×10^6 V/m.

The MAGIC simulations showed an interaction resulting in a scattered wave at $\omega = 2\omega_p$ for a plasma containing the beam-plasma instability. There is no interaction if the plasma does not contain the beam-plasma instability. The field component at $2\omega_p$ is seen to increase as γ_o is increased. The increase is due to an increase in the plasma turbulence resulting from the larger Lorentz factor. For large electric field strengths (4.25×10^6V/m) the incident wave perturbs the plasma density, and reduces the coupling and the scattered wave.

1.4 Recommendation for Further Study

The coupling of the incident wave with the beam-plasma instability induced electromagnetic turbulence should be studied further. In particular the angle dependence of the incident wave wavevector on the coupling should be investigated. Conservation of momentum is important in parametric instability, thus the vector sum of the incident wavevector and the wavevector of the electromagnetic turbulence should play a critical role in the strength of coupling. With the present version of the MAGIC code, the wavevector of the injected wave is limited to perpendicular incidence with the direction of the beam, limiting the ability to study coupling strength versus wavevector orientation.
The newest release of MAGIC contains a command call ADRIVER which could possibly be used to vary the direction of the incident wave wavevector. The localized geometric effect of the beam on the beam-plasma instability should also be further studied. A high density localized beam could cause particle bunching transverse to the beam producing fields in the transverse direction, possibly affecting the electromagnetic nature of the beam-plasma instability. The simulations contained herein had a beam to plasma number density of $\frac{n_b}{n_p} = .02$ which is relatively small and transverse bunching was not observed. A simulation with a beam to plasma number density of $\frac{n_b}{n_p} = .2$ was conducted and larger transverse field were observed. The effect of the transverse fields on the beam-plasma instability should be investigated.

Part II: Investigation of a Deflecting Relativistic Klystron Scheme.

Research assistants: C.K Axton
V.J Tyson
Supervisor: Dr. K. W. Zieher

2.1 Introduction

High efficiency microwave generation plays an important role in radar systems and communications. Most medium and high power microwave generators make use of the high power density achievable in a charged particle beam. The energy of the charged particles is coupled to the electromagnetic fields through the Lorentz force. The most effective energy transfer is achieved if the particle beam is density modulated with the frequency or a subharmonic of the frequency of the microwave field. Either an electron beam is generated already in bunches by source modulation or the flow of an initially constant beam is modulated by an appropriate bunching scheme.

The power density which can be carried by a charged particle beam is limited by the defocusing due to the self-fields. In a nonrelativistic particle beam the electrostatic defocusing dominates the self-magnetic focusing. As the particles approach relativistic velocities the two force contributions will mutually cancel. As the beam gets bunched the self-forces for a nonrelativistic particle beam will become even more significant. At the same power density the charge density in a high energy charged particle beam is smaller. This means that a relativistic particle beam is much easier to transport. This requires less power in the focusing solenoid, which is according to Gilmour [1] the main penalty in efficiency for a linear beam tube.

Further, the power requirements for the cathode of the electron beam source become rather modest. Instead, the electrons have to be accelerated to a larger velocity which requires a high-voltage supply with the same power as for nonrelativistic beams but higher terminal voltage at lower current. To some extend the problem is shifted from the microwave source to the high-voltage generator. High-voltage generators, especially pulsed modulators, are well developed.

The bunching can be achieved for nonrelativistic electron beams by periodic speed modulation in a buncher section and a drift space. The accelerated electrons are faster and catch up with the ones slowed down. The buncher and the drift space can overlap like in a traveling wave tube or be separated like in a conventional klystron [2]. For relativistic particle beams the speed can not be modulated significantly since it is close to the speed of light. For a relativistic electron beam the velocity change is quite small

$$\delta v/v = 1/(\beta^2\gamma^2)\cdot(\delta\gamma/\gamma)$$

where $\beta = v/c$ and γ is the relativistic factor. In this case velocity bunching is not effective except if the electron current approaches the space charge limit which would be of the order of tens of kA. Then some novel space charge effects help modulate the electron current [3]. For lower currents one rather has to modulate the relativistic momentum and use a momentum dependent transport system like a magnetic deflecting field.

A buncher for relativistic electrons has been suggested by F.S. Felber et al. [4]. It uses a toroidal wave superimposed on a transverse magnetostatic field. The energy is modulated by the toroidal electric field component of the RF wave. The increase of longitudinal momentum gives a larger Larmor radius and therefore a longer trajectory for the higher energy electrons and leads to a retardation of the higher energy electrons (negative mass effect). By harmonic modulation of the energy one can get bunching of the electrons even for relativistic particles.

In the following a microwave generator system is described which uses transverse momentum modulation and subsequent deflection of a relativistic electron beam in a static magnetic field to achieve bunching without energy modulation.

2.2 Concept of the deflecting extended interaction klystron

The bunching principle goes back to Mobley in 1958 [5] who suggested transverse momentum modulation and subsequent magnetic deflection for production of monoenergetic ion pulses. Instead of modulating the energy, the transverse momentum of the charged particles is modulated. This results in a periodic deflection of the electrons from their reference trajectory and leads to bunching due to the different path lengths. A schematic layout of a deflecting extended interaction klystron is shown in Figure 5.

A high voltage generator is driving a high impedance electron source. The unmodulated electron beam will traverse one cell of a multi-cell cavity resonator transversely so that the electric field will cause a transverse deflection. Subsequently the beam particles will travel on different trajectories according to their transverse momentum and position. The path length varies accordingly in the 270-degree deflecting magnet. The use of a transverse deflector will not change the energy of the particles to first order if the transverse electric RF field is used. Using deflection of the electrons by the magnetic RF field will not change the energy of the electrons and the deflection is only smaller by the factor $\beta = v/c$. After an appropriate distance the beam particles on a shorter trajectory will catch up with the particles with a longer path length. The electrons will concentrate in equally spaced bunches. These bunches will enter the multi-cell RF resonator along its axis. The electric field intensity near the axis will slow down the electron bunches. The change of the kinetic energy of the electrons is converted into RF field energy.

The scheme can be used as an oscillator where the modulating cavity is part of the decelerating multi-cell structure and traversed twice. In this case the frequency can be

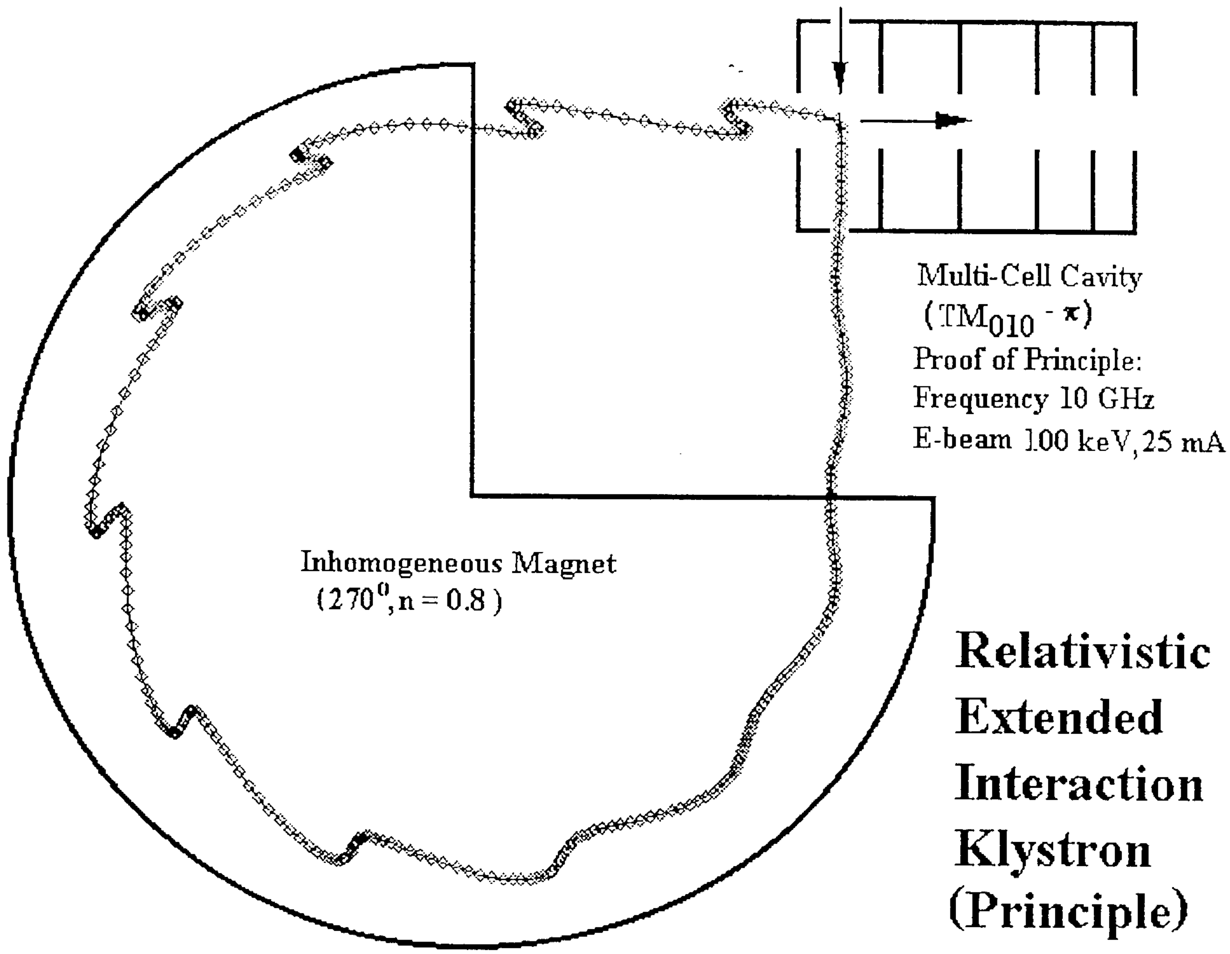

Figure 5. Scheme of the Deflecting Relativistic Klystron

controlled by the magnetic field intensity of the 270° deflecting field within the bandwidth of the multi-cell resonator. Another mode of operation is as an amplifier, by driving the buncher cavity from a signal source. The buncher does not impart any energy on the particles (and this not only in the average as in a conventional bunching scheme). The input losses are only the resistive losses in the buncher cavity.

The deceleration process is the inverse of the dynamics in a linear accelerator. Longitudinal phase stability can be achieved within a longitudinal acceptance area which depends on the synchronous phase ϕ_S. The stable phase interval approaches a length of approximately $3\phi_S$ as the particles slow down. The decelerating field is on the average $2E_0 \cos\phi_S /\pi$. The phase of the synchronous particle is $\phi_S = 30^o$ and is kept constant for simplicity. The efficiency might be improved by changing the synchronous phase along the decelerator from an initial value close to 0^o to a value around 45^o towards the end of the decelerator. The self-fields of the electron bunches are not critical for the investigation even if one would go up to an average current of 20A at an initial electron energy of 1 MeV. At this current and longitudinal space charge effects would become noticeable. For a 100 keV electron beam this translates to a current of 0.5 A .

The efficiency of a microwave tube can be significantly improved by particle energy recovery of the spent beam. Having no initial energy spread in the bunched beam is a good starting point for later energy recovery. In more exact terms, it is the initial longitudinal phase space volume which can not be reduced and will limit energy recovery of the spent beam. Varying the synchronous phase periodically between $+\phi_S$ and $-\phi_S$ will give simultaneous longitudinal and transverse focusing inside the decelerator, which is known in accelerator theory as variable phase focusing. This would keep the energy spread of the decelerated electron bunches to a minimum and improve energy recovery. These possible improvements have not been investigated further.

2.3 Numerical Simulation

The original klystron scheme using a 1 MeV electron beam was simulated with a single cell cavity at 10 GHz. In the simulation the cylindrical cavity was replaced by a rectangular cavity since the MAGIC code allows only a two-dimensional geometry. The field distribution in the rectangular cavity differs significantly from that in a cylindrical cavity. Still the simulation should indicate any difficulties in running the system as an oscillator. The simulation showed that a seeded oscillation would grow to a saturation level and then be sustained stationary. Figure 6 shows the growth of the field amplitude in the cavity as a function of time. A spectrum of the oscillating field was derived and is shown in Figure 7. Figure 8 shows a snapshot of the electron beam after the system is oscillating stationary.

A 2-dim particle-in-cell simulation (using again the MAGIC code) of the whole bunching and deceleration process for a 100 keV electron beam and a single-cell decelerator has been performed and showed similar behavior as the scheme using the 1MeV beam. In the simulation the cylindrical cavity was again replaced by a rectangular

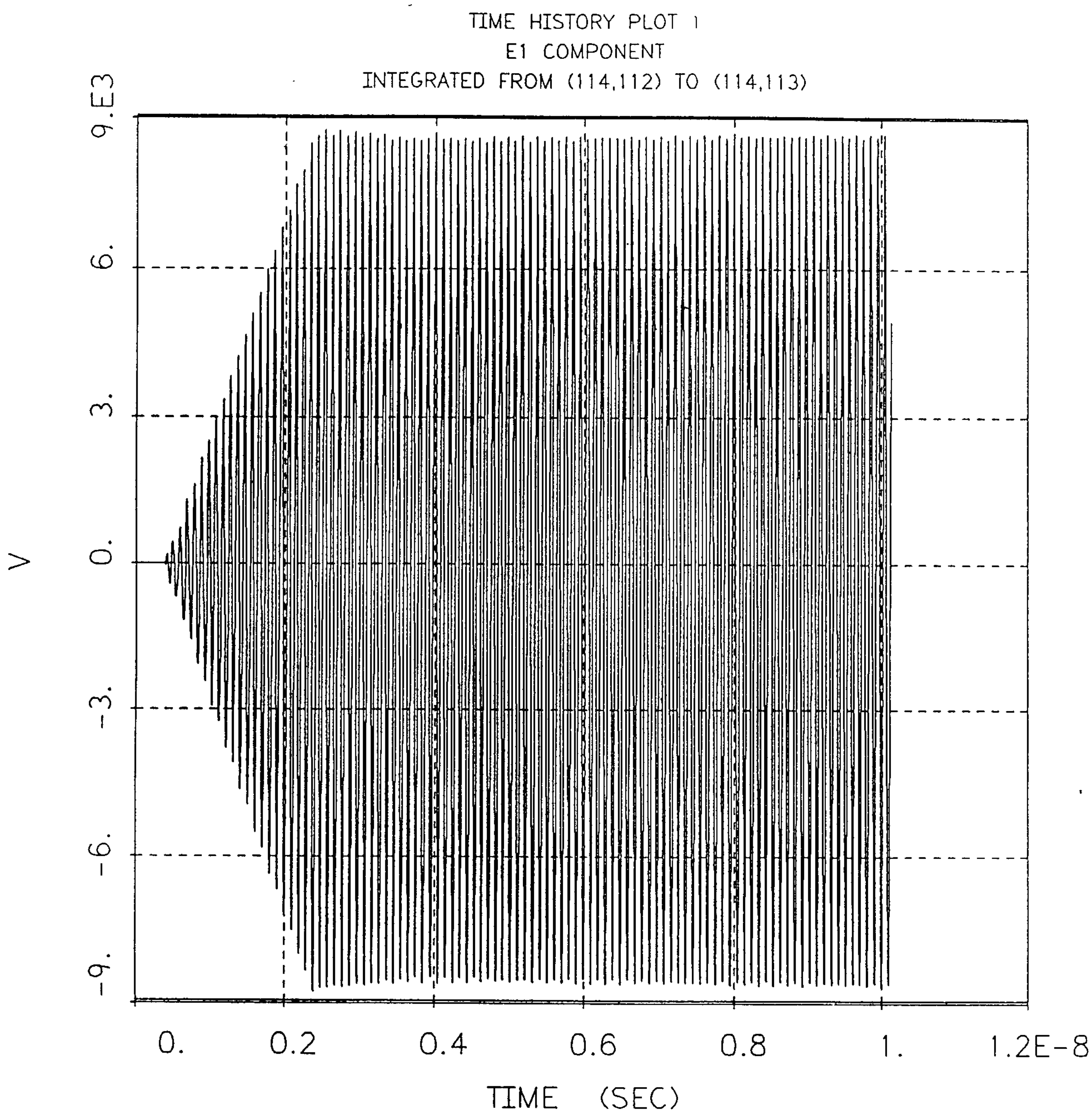

Figure 6. Time History Plot of Electric Field in the Cavity for 1 MeV Electron Beam

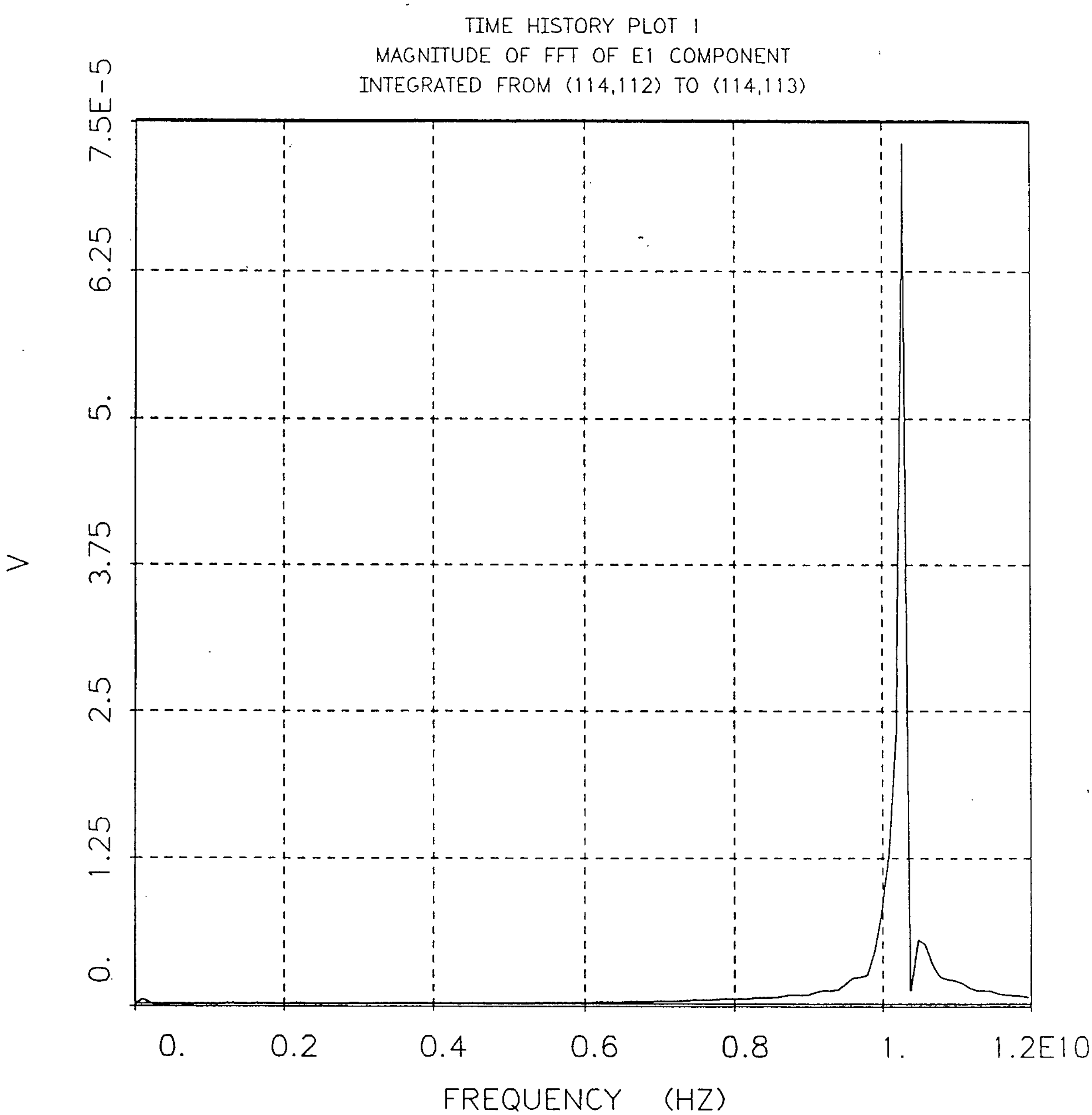

Figure 7. FFT of the Electric Field in the Cavity for a 1 MeV Electron Beam

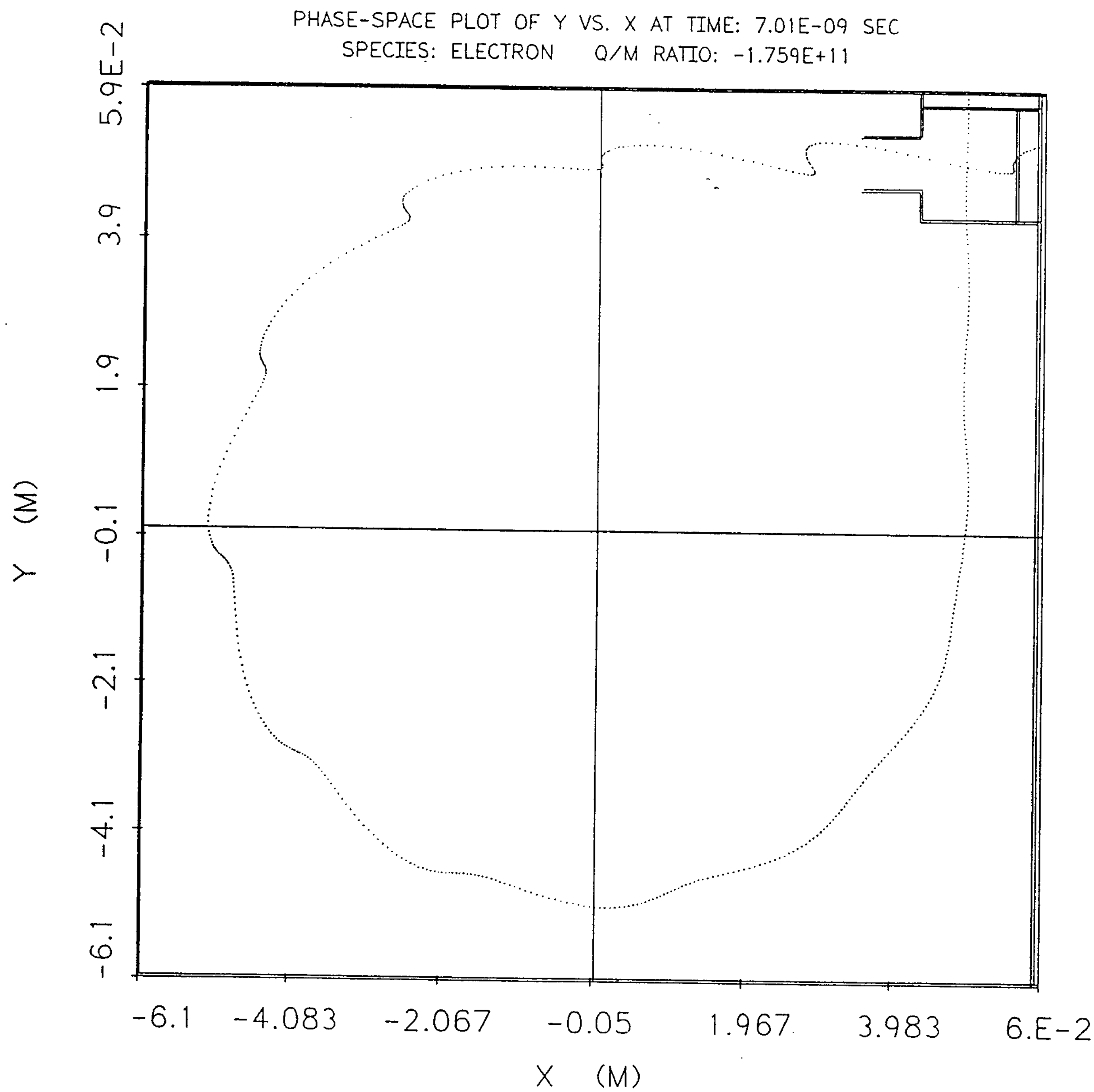

Figure 8. Electron Position Plot for 1MeV Electron Beam

cavity. Oscillations were observed. Figures 9, 10, and 11 show the growth of the RF field, the spectral density, and a snapshot of the electron beam respectively.

2.4 Experiment

A one-cell cavity for 10 GHz was built. Measurements on this cavity were performed to get the student familiar with the measurement methods and to test the quality of the joint in the cavity. The first attempts produced low quality cavities. The quality factor was of order Q = 70. This improved with better clamping and subsequently by soft soldering the joint. Figure 12 shows the response of a one-cell cavity as a function of frequency for a soft soldered cavity.

To couple the power in and out of the cavity a very thin coaxial line with a small loop at the end is introduced about a mm into the cavity. The coaxial line has an outside diameter of 1.25 mm. The coupling factor was determined by measuring the reflection factor. A correction to the loaded cavity quality factor gives the best quality factor achieved for a soft soldered cavity of about 1300. There could be additional losses at the contact between the coaxial line and the cavity wall. As a next step silver soldered single cell cavity was built and the resonance curve measured. The quality factor of Q = 7800 was achieved which is closer to the theoretical value of Q = 8800 for an unloaded copper cavity.

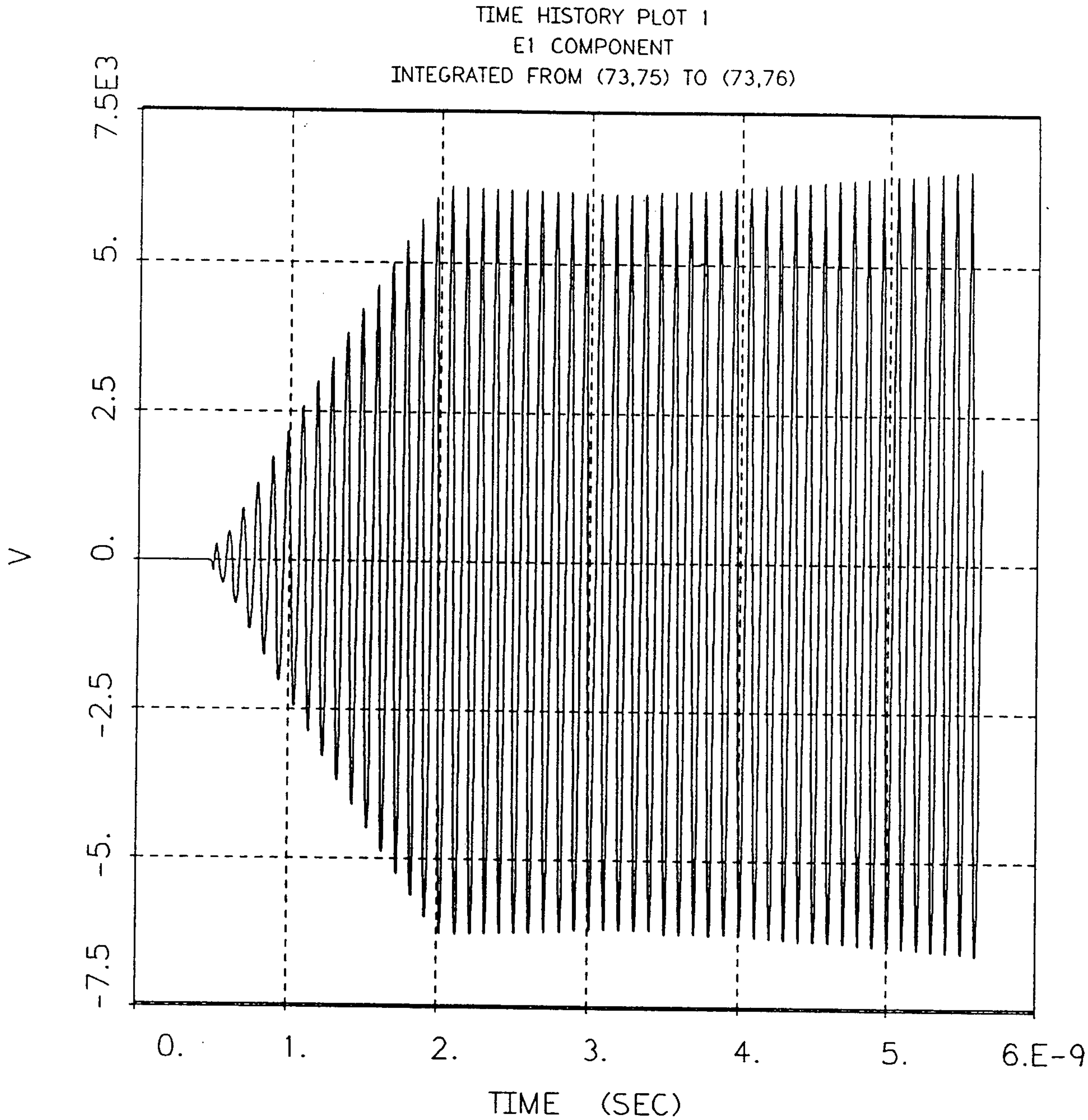

Figure 9. Time History Plot of Electric Field in the Cavity for a 100keV Electron Beam

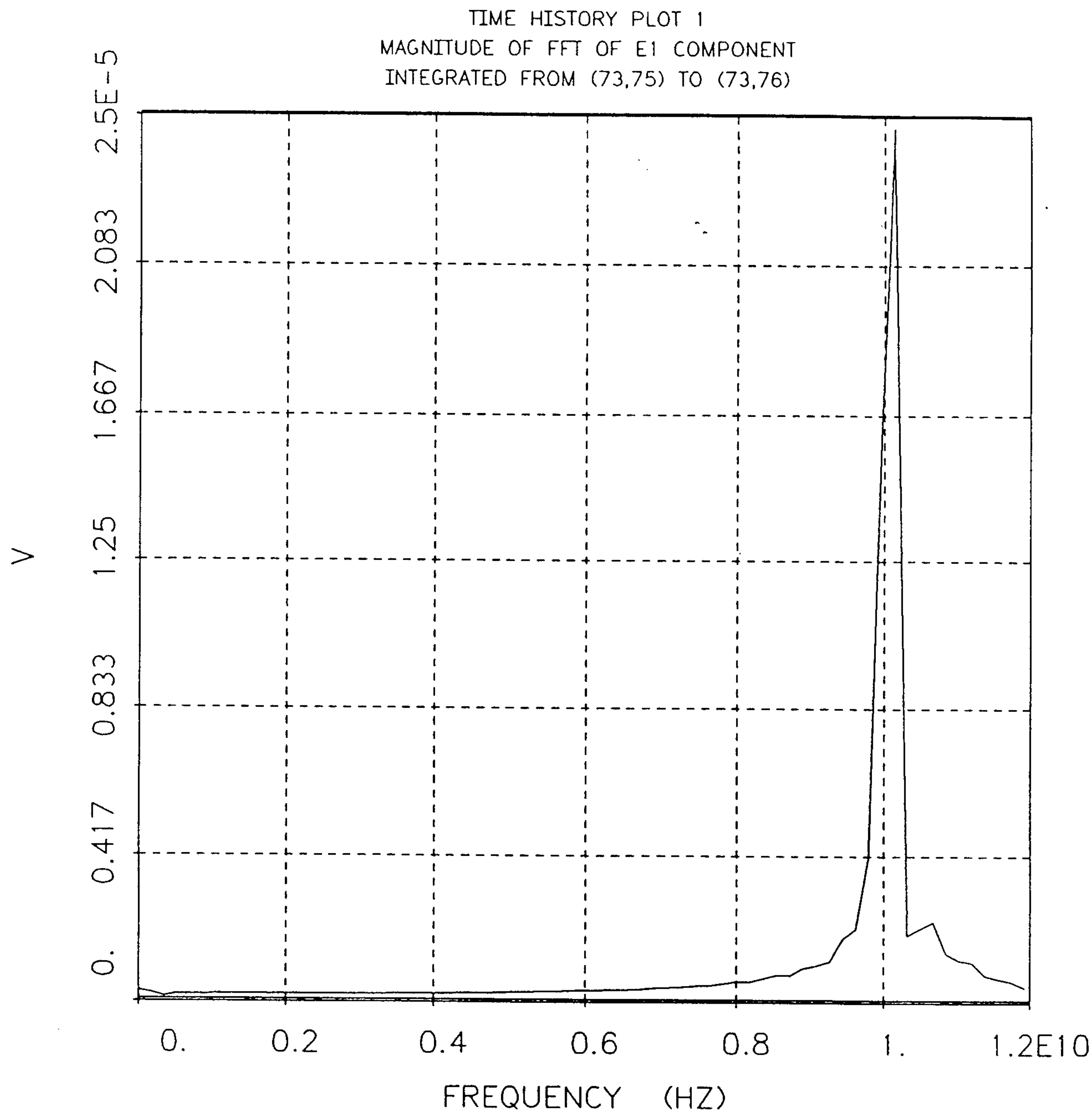

Figure 10. FFT of Electric Field in the Cavity for a 100keV Electron Beam

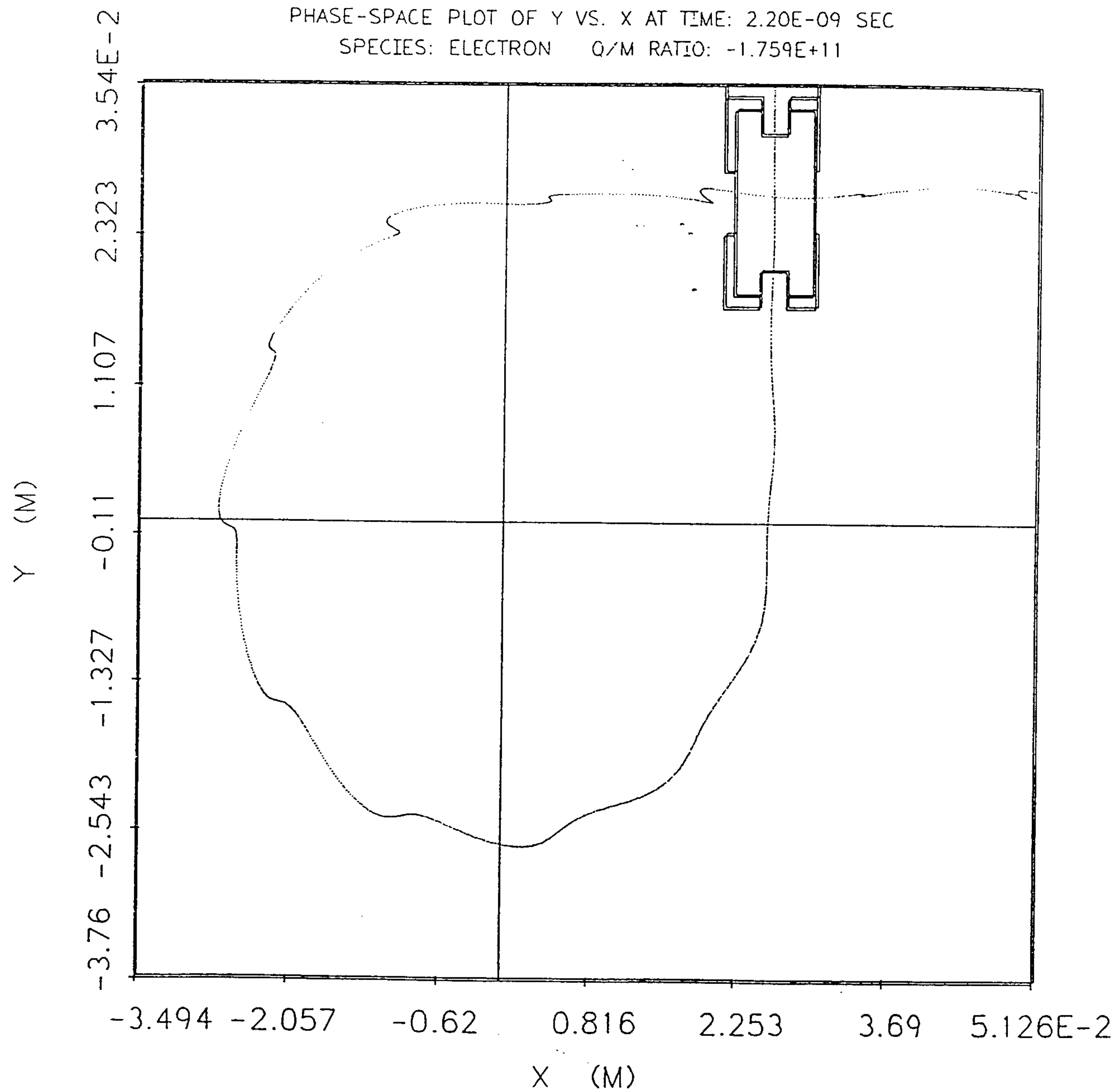

Figure 11. Electron Position Plot for a 100 keV Electron Beam

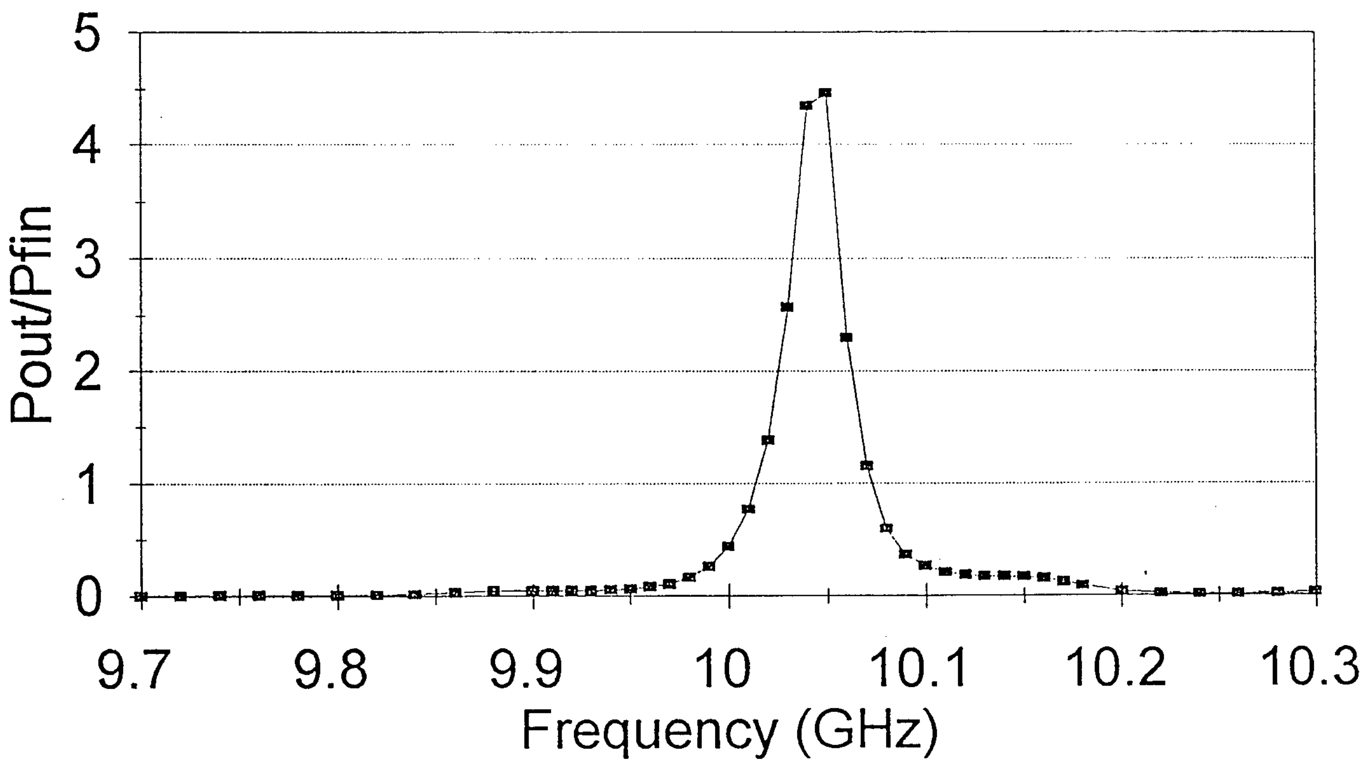

Figure 12. Measured Frequency Response of a Single-Cavity Clamped Cavity

3. Summary

MAGIC has been used to study the electromagnetic nature of the beam-plasma instability and the interaction of an incident electromagnetic wave with beam-plasma induced turbulence. From the conducted study the following conclusions can be made.

a) The electromagnetic nature of the beam-plasma instability has been verified with two-dimensional particle simulation. The growth rates of the electromagnetic field energy from the numerical experiments have been compared to linear theory and agree with theory both as function of beam velocity and wavenumber.

b) The beam-plasma instability saturates, as seen, through saturation of particle kinetic energy and plasma field energy. The saturation has been seen to be consistent with quasi-linear theory as verified through the plateauing of the beam velocity distribution and trapping of the beam electrons.

c) The generation of electromagnetic turbulence from the relativistic beam-plasma instability is found to couple into an incident electromagnetic wave, with frequency ω_p, and produce scattered electromagnetic radiation at $\omega = 2\omega_p$.

d) The electromagnetic scattering is consistent with theory. The strength of the coupling is seen to be a function of beam Lorentz factor which is also consistent with theory.

e) The coupling falls of abruptly as the incident wave frequency is moved away from the plasma frequency.

f) There is no coupling when the plasma is not exposed to the beam-plasma instability.

The electromagnetic nature of the beam-plasma instability has been verified by particle simulation. Scattering of an incident electromagnetic wave from $\omega = \omega_p$ to $\omega = 2\omega_p$ has been shown to take place in the presence of beam-plasma induced turbulence.

Numerical simulation using the code MAGIC were performed using a two-dimensional scheme of the deflecting relativistic klystron.

a) The theoretical expectations of the relativistic klystron scheme were confirmed by numerical simulation. The simulation indicates that this klystron system will oscillate at the desired frequency for a 1 MeV electron beam as well as for a 100 keV electron beam.

b) Single-cell cavity measurements gave a quality factor close to the theoretical value. The results of the cavity measurements will directly influence the research done under the DoD MURI program AFOSR grant # F49620-95-1-033.

Publications

"Two-Dimensional Particle Simulation of Relativistic Beam-Plasma Electromagnetic Instability", J. Masten and O. Ishihara, IEEE Transactions on Plasma Science (in press)

Conference papers

"Relativistic Beam-Plasma Instability and Its Interaction with Electromagnetic Wave", J. Masten and O. Ishihara, APS Texas Section Fall Meeting, (October 27-28, 1995, Lubbock, TX).

"Photon Interaction with Beam-Plasma Induced Electromagnetic Turbulence", J. Masten and O. Ishihara, IEEE Int. Conf. on Plasma Sci. (June 5-8, 1995, Madison, WI).

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"MAGIC Simulation of Relativistic Electron Beam Interaction with Hot Plasma, J. Masten and O. Ishihara, Bull. Am. Phys. Soc. **38**, 1994 (1993).

"Relativistic Electron Beam-Plasma Instability and Interaction with Electromagnetic Wave", J. Masten, Dissertation , Texas Tech University, Department of Electrical Engineering, Lubbock, TX 79409 (December, 1995)

"Investigation of a Deflecting Relativistic Klystron Scheme", C.K. Axton, Y. Liu , D.L. Roye, J.H. Rybicki, V.J. Tyson, and K.W. Zieher, AMEREM 1996 ,(May 27-31, 1996, Albuquerque, NM), (poster)

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