MICROWAVE AND ACCELERATOR RESEARCH

ANNUAL REPORT FOR PERIOD JUNE 1 1992 - PRESENT

ON

GRANT DE-FG02-92ER40731

RECEIVED
JUN 01 1993
OSTI

Prepared by:

John A. Nation
Laboratory of Plasma Studies & School of Electrical Engineering
Cornell University, Ithaca, NY 14853, USA

Table of Contents

Introduction

This report describes work carried out on DOE grant number DE-FG02-92ER40731 during the period June 1 1992 to the present. The report provides a brief summary of the program objectives, summarizes the main accomplishments and concludes with listings of conference and refereed publications.

Technical Program

Microwave Research: The purpose of this research program is to investigate the production and physics of ultra high power microwave sources which may have applicability to future generations of electron-positron linear colliders. The work is a continuation and an extension of an earlier DOE sponsored research program.

The next linear collider will require the successful development of ultra high power microwave sources. The sources must not only be very efficient and inexpensive but also must be phase stable. Peak powers of several hundred megawatts are required in X band in pulses of order 170 ns. to drive accelerator modules with lengths of a few meters. Our recent research program has focussed on the generation of radiation at 8.76 GHz using a traveling wave tube amplifier (The frequency was dictated by the availability of a magnetron and not by other considerations). Peak powers of up to 400 MW were obtained at an efficiency of over 40%. The sources were however limited in utility as a result of the development of sidebands which carried up to 50% of the radiated power. During the current grant period our efforts have focussed on the design of systems to eliminate the sideband phenomenon. The origin of the sidebands has been traced to finite structure length effects which result in low Q structure resonances. The resonances are a consequence of small impedance mismatches at the input and output ends of the amplifiers. Interactions and wave growth occur at frequencies corresponding to the preferred wavenumbers. At power levels of over about 70 MW we find that the sidebands develop and increase in importance as the power is increased.

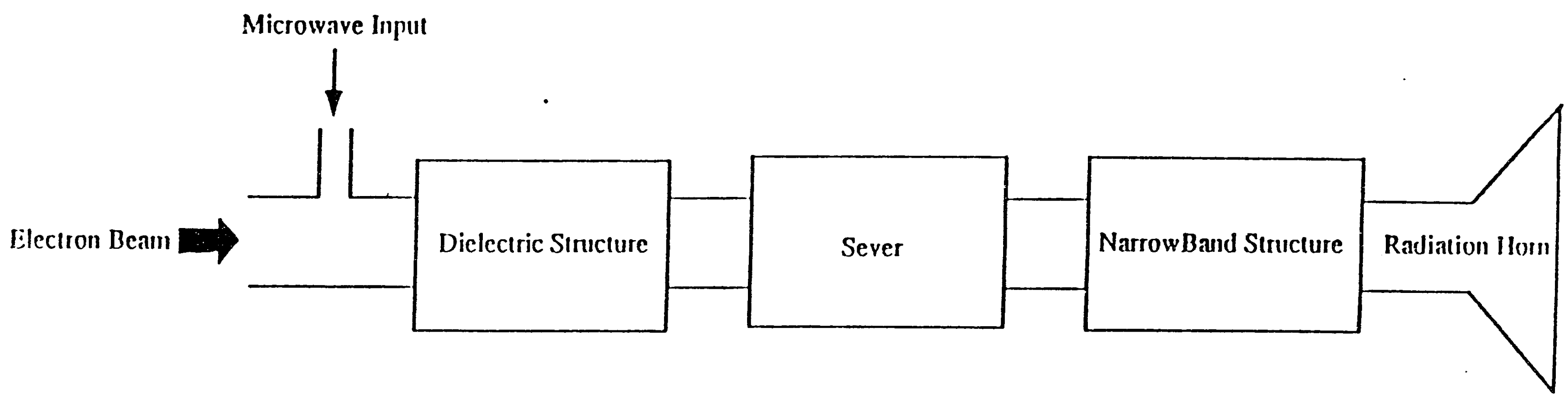
Attempts to increase the structure gain above 35 dB lead to oscillation of the amplifier. To overcome this problem we developed a severed two stage amplifier in which the gain could be further increased, reaching ultimately a power output of 400 MW at an efficiency of over 40 %. In the two stage device the first stage produces gains of over 30 dB and leads to bunching of the beam with a substantial broadening of the electron momentum spectrum. The electromagnetic wave is cut-off in a severed section and then reconstructed from the bunched beam in the second stage. The broad momentum spectrum of the entering electrons leads to wave growth at the preferred wave numbers (determined by the low Q structure resonances) adjacent to the resonant value for the cold beam. The development of sidebands is evident at all output powers in the two stage device.

We have developed a solution to the sideband problem based on the use of a slow wave structure with a very low group velocity. In such a structure the TWT may be thought of as a series of weakly coupled cavities. Preferred wavenumbers should be significantly less important in these devices as the input is isolated from the output for a time equal to the structure length divided by the group velocity. This time is comparable to but somewhat less than the rf pulse duration, consequently the cavity does not get a chance to establish preferred values of the wavenumber. In addition the wave is highly attenuated in transit through the structure much like the regime found in klystrons where the cavities are isolated from each other by extended cut off sections of guide. For the forward going wave the electron beam couples adjacent cavities so the poor coupling in the absence of the beam is of no importance. Finally we note that we have simulated these new structures using the MAGIC code. Results from the simulations confirm that the new structure will eliminate the sidebands.

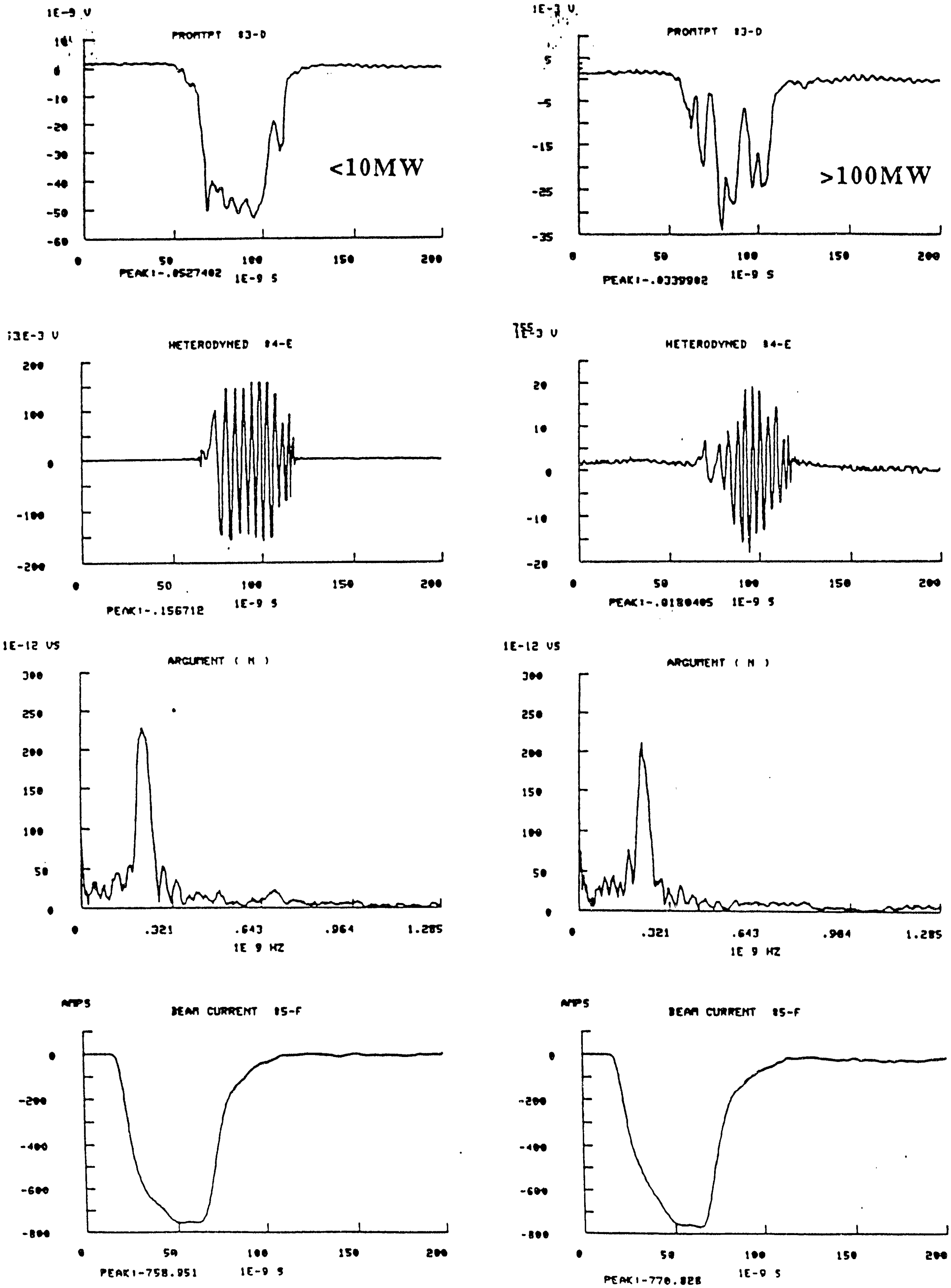
Our new experimental configuration is shown schematically in figure 1. The amplifier is a two stage device which, in our opinion, offers the best chance of successful operation. The first stage consists of a dielectric amplifier which was chosen for its broad band characteristics and because it is relatively straightforward to avoid reflections from the output section. The first stage is separated from the narrow band amplifier second stage by a sever which substantially attenuates the electromagnetic wave but readily permits propagation of the modulated beam generated in the first stage. The electromagnetic wave is reconstructed in the second stage amplifier and grows rapidly to a very large amplitude. The sideband growth is effectively suppressed since the sidebands are so close in frequency to the input frequency that they fall within the natural bandwidth of the amplified wave. Further detail describing this process may be found in the theoretical section of the report. Figures 2 and 3 show typical waveforms from the experiment at low and high powers, and a frequency response for the composite amplifier. Note the narrow frequency range for which we have high output power in comparison with the open circles which show the power from the dielectric amplifier only. In addition we draw attention to the differences between the low power and high power output pulses. The fluctuations in the high power pulse are as yet not understood and will be the subject of further investigation in the coming year. Observe, however that there is no evidence of sideband radiation evn in the high power data. Work is also in progress on the development of a cavity drive for the first stage to replace the dielectric amplifier. To date we have demonstrated beam modulation in a cavity powered at the 10 kW level. An amplifier has been designed to work with the modulated beam and is in fabrication.

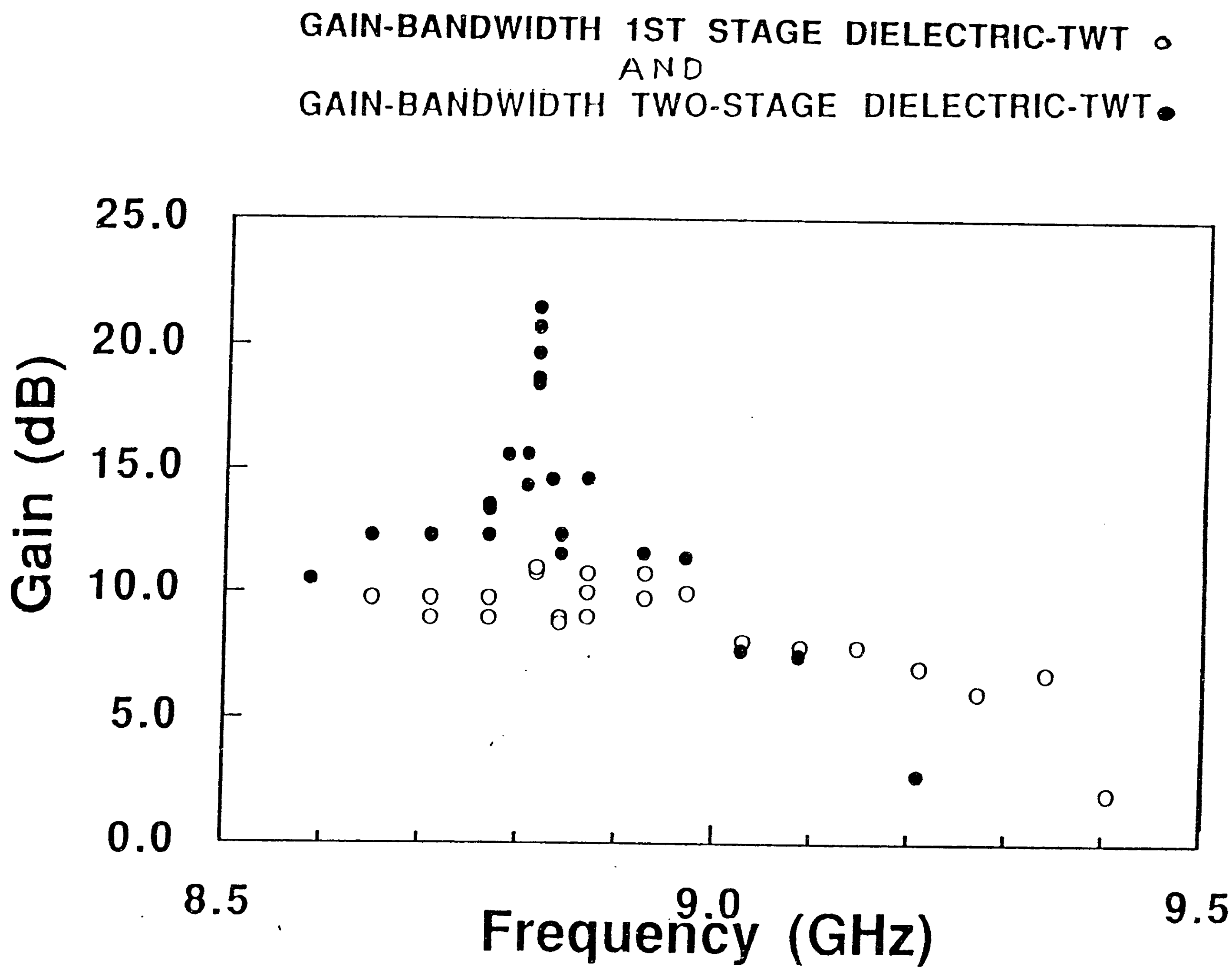
Repetitive Source Development: We have initiated an effort during the last year to obtain compact low repetition rate modulators to drive electron beams for microwave generation experiments. Our long range goals are shown in the table on the following page. We expect to commission the first phase device during the current calendar year. It is based on the circuit shown in figure 4 and uses a ferrite loaded cable transformer. An output waveform is shown in figure 5 which overlays several shots. The output pulse is flat to better than 1% over the 120 ns flat top of the pulse. In the phase two program we will attempt to stack multiple transformer modules in series to obtain operation at output voltages of up to 500 kV.

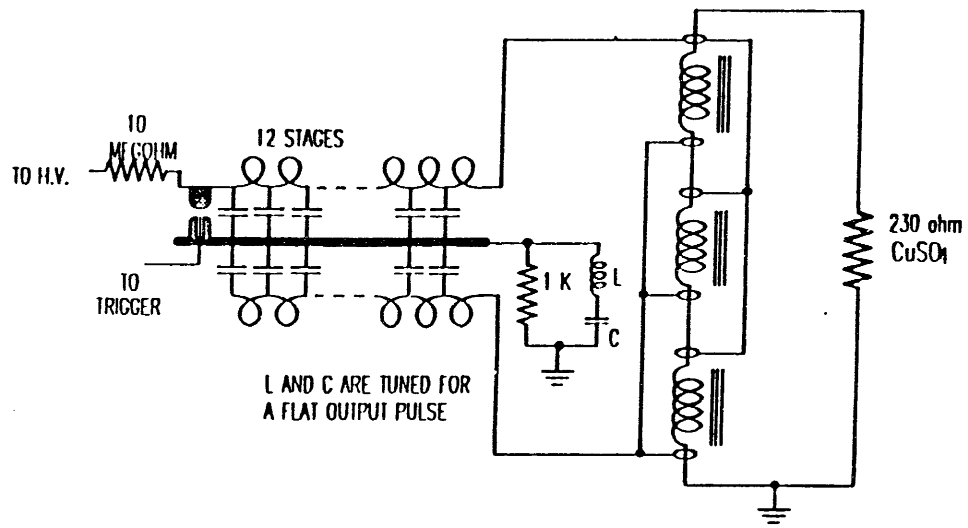
TWO-STAGE NARROW BANDWIDTH DIELECTRIC-TWT



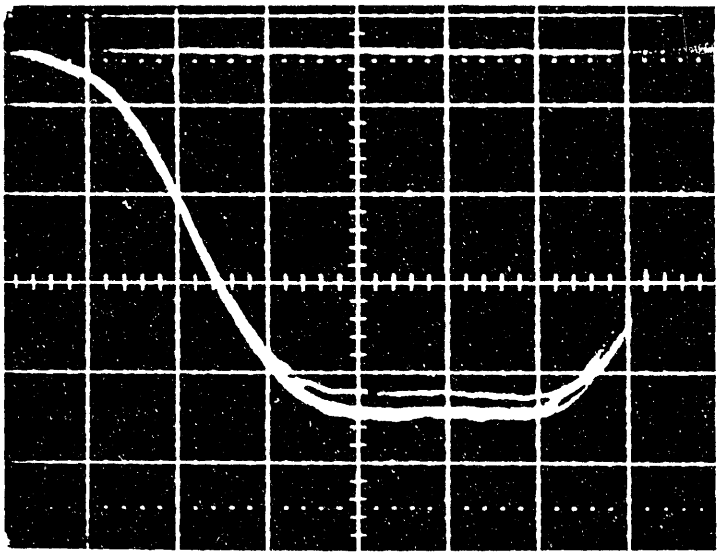
TWO-STAGE NARROW BANDWIDTH AMPLIFIER




GAIN-BANDWIDTH 1ST STAGE DIELECTRIC-TWT o
AND
GAIN-BANDWIDTH TWO-STAGE DIELECTRIC-TWT ●
Gain (dB)
25.0
20.0
15.0
10.0
5.0
0.0
8.5
9.0
9.5
Frequency (GHz)



THREE TO ONE PULSE TRANSFORMER MODULE



Vertical	11.7 kV / div
Horizontal	50 ns / div
Pulse Line	54 J
V - Charge	12 kV
Load	500 Ohms on secondary

Modulator and RF Source Characteristics

	Phase 1.	Phase 2.	SLAC Proposal
Modulator			
Energy Stored (J)	35	100	500
Charging Voltage (kV)	40	50	80
Transformer Ratio	3	3	6
Modules	1	2	1
Output Voltage (kV)	120	300	500
Output Current (A)	600	800	600
Pulse Duration (ns)	250	250	1500
Efficiency (%)	50	60	80
Repetition Rate (Hz)	1	1	180
RF Source			
Output Power (MW)	35	120	400
Pulse Compression	1	1	6

A phase three willl follow in which the operating voltage of each module is increased to 80 kV and the output pulse to 500 kV allowing for a 200 MW rf output power.

The modulator just described will be used in conjunction with our recently developed ferroelectric electron sources which will be used as the cathodes for the beam generation. As indicated above we expect to run beam diodes in the current calendar year and extract the beam into a meter long axial magnetic field for rf experiments in the following year. For radiation safety considerations we shall restrict operation to about 1 Hz.

Theoretical Studies: The theoretical effort towards development of high power microwave (HPM) sources during 1992 covered the 5 topics which are listed below:

(1) Amplifier Oscillator: A Unified Study
(2) Narrow Band Structure: A Solution to the Sidebands Problem in HPM-TWT
(3) Electron Beam Generation Using Ferro-electric Ceramics
(4) Interaction of an Annular Electron Beam with a TM Mode in the Presence of a Longitudinal Wiggler (TM-FEL)
(5) Passive and Active Quasi-Periodic Structures

In this report we shall review the main results of each topic. Items 1,2 and 5 deal directly with high power sources while item 4 introduces a new source concept. The remaining item describes theoretical studies in support of our ferroelectric experiments. Details of the work are presented in the publications which are listed at the end of this report. The full reports were recently provided to DOE during their site visit on January 25 and 26.

Amplifier and Oscillator: A Unified Study. The experimental results on high power microwave generation in the past years indicated that power levels from a two stage amplifier could reach the $400MW$ level with an efficiency of almost 50% but with a broad spectrum (more than $300MHz$ wide). In fact about 50% of this power was in sidebands which were asymmetric relative to the frequency of the input signal - ruling out the possibility of a non-linear effect being responsible to their development. This kind of output is inadequate for accelerator applications. Theoretical studies of the sidebands has indicated that they are result of three simultaneous processes in the amplifier: (i) a large electron velocity spread develops in the interaction process. This induces in the system a broad noise spectrum according to the electromagnetic characteristics of the slow wave structure. (ii) The electromagnetic noise is amplified by the beam itself and, (iii) The reflections from both ends of the interaction region cause an interference effect between the two bouncing waves. This in turn is revealed as a frequency selection process namely, energy in certain frequencies is preferentially transmitted forward.

The tools for the understanding of this model were developed during 1991: basically we developed a model for the interaction in a TWT based on a single particle equation of motion (macro-particle model). This allowed us to clearly show the wide energy spread in the interaction process - when reflections were ignored. As indicated above, this velocity spread can generate in a broadband periodic structure a wide noise spectrum. Once this noise was understood the remainder is a straight forward analysis of a linear system fed by a signal and noise. It was quite evident at this point that the usual approach in which the reflections are neglected when describing amplifiers is not adequate. Furthermore the frequency selection (interference effect) associated with this process clearly resembles the operation of an oscillator. For these two reasons we developed a model which in addition to the variation in space(1D), and in time, of the amplitude of the electromagnetic field, we introduced an additional equation which represents the feedback due to reflections. This equation relates the amplitude at the input end at any time with the amplitude at the output end delayed by the time it takes the electromagnetic energy to travel one length of the structure. Using this set of equations we were able to show (among other things) that in addition to the asymmetric sidebands discussed above there are also symmetric sidebands which are a result of the variation in time of the amplitude of the wave at the input.

Narrow Band Structures: The time it takes the wave which is reflected from the output end to reach the input is determined primarily by the energy velocity - which is the ratio between the average power flowing in the system and the average energy stored per unit length. Therefore, one can design a structure which has a low energy velocity such that by the time the first reflection approaches the input the electron pulse has ended. An alternative way to describe this process is based on the dispersion curve of a periodic structure. If the pass band is wide (say $1.5GHz$ as in the original experiment) then if the velocity spectrum of the electrons is between $0.8c$ and c, the width of the noise spectrum is about $300MHz$. If we now design a structure which has an entire pass-band of $200MHz$ then the noise can be emitted at the most in a range of $30MHz$. In other words the noise spectrum and the signal overlap so no sidebands will occur. Such a structure was designed and tested. The preliminary theoretical results indicate that the gain per unit length is typically $6dB/cm$ compared to $1dB/cm$ in the original structures. The efficiency can be as high as 50% but the electric field on the disk loaded structure exceeds $200MV/m$ for power levels of more than $200MW$. At the Port Jefferson meeting we reported two MAGIC simulations of wave growth with wide and narrow band structures which showed that the sideband problem was solved by use of the narrow band slow wave structure. Recent experimental results support this conclusion.

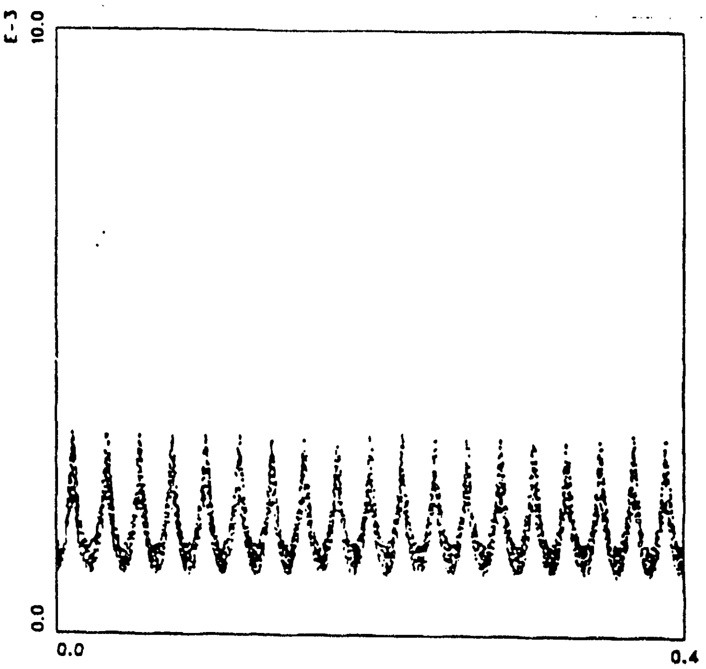
Electron Beam Generation Using Ferro-electric Ceramics: The results from the ferro-electric experiment indicate that current densities of more than (*i*) $30A/cm^2$ can be generated from a ferroelectric with a voltage of up to $600V$ applied on the anode (gap $2-10mm$). (*ii*) The current duration is controlled primarily by the the anode voltage. If we use the numbers above to determine the Child-Langmuir limit we would find that the current exceeds the limit by two orders of magnitude. In principle the use of this formula is misleading since it assumes that the electric field at the cathode surface is zero; a condition violated in this system - at least in the regime we are discussing. The applied anode voltage causes electrons already in the gap to traverse it, but does not contribute to the emission. The electrons are present in the gap as a result of a potential applied to the rear electrode of the ferroelectric (the front electrode is gridded and grounded). In order to understand the redistribution we have to bear in mind that the polarization field in the material is screened by a layer of free charge - in the experiment the screening layer facing the gap consists of electrons. When a voltage is applied to the rear electrode the polarization field is altered and less electrons are required for the screening process. This fact in conjunction with the electrostatic coupling between the ferro-electric and the gap through the grid (which in turn generates the field which extracts the electrons from the metallic grid) , causes a fraction of the electrons to be redistributed in the gap.

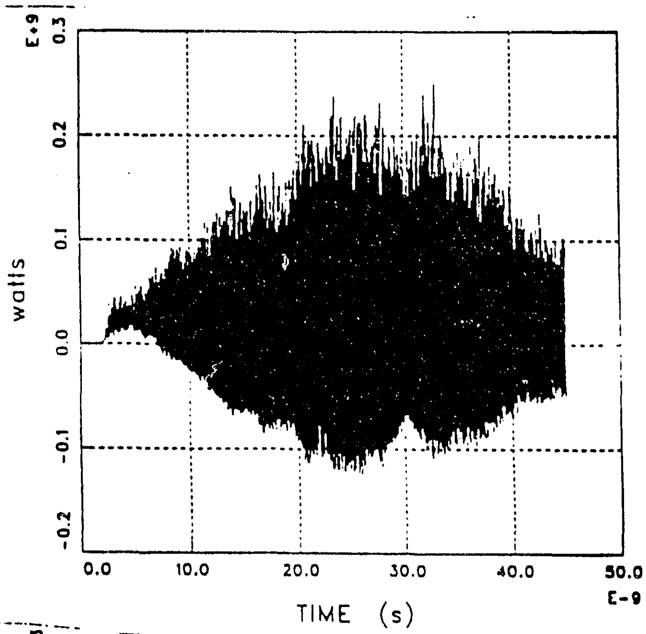
TM Mode interaction of an Annular Electron Beam with a Longitudinal Wiggler: One of the drawbacks of disk loaded TWT structures is their susceptibility to rf breakdown at high power levels. This problem is practically eliminated in free electron lasers (FEL) by use of a smooth waveguide. The problem in this case is that the electrons oscillate perpendicular to the major velocity component (rather than parallel as in the TWT). We have shown that the coupling coefficient (adequately normalized) scales like $1/(\gamma\beta)^5$ in the FEL and $1/(\gamma\beta)^3$ in TWT - because of the direction of oscillation. (A similar power ratio holds for the spontaneous radiation emitted by charges accelerated perpendicular or parallel to the velocity.) So the immediate question is whether one can force the electrons to oscillate primarily in the longitudinal direction using a wiggler - we call the device TM-FEL. We found that this is possible if one uses a "longitudinal" wiggler so that the electrons interact with the TM mode as in a TWT and unlike that in the regular FEL where the interaction is transverse and couples to a TE mode. It was demonstrated that the equations of the TM-FEL are practically identical to those of the TWT. In Fig.6 we present three frames: the first shows the trajectory of the electrons, the second illustrates the output power ($100MW$ average and $200MW$ peak) and the final frame indicates that the spectrum of the output signal. The operating regime is at low energy velocity so that the coupling is strong as in the case of the Narrow Band TWT amplifier. The wiggler is determined by

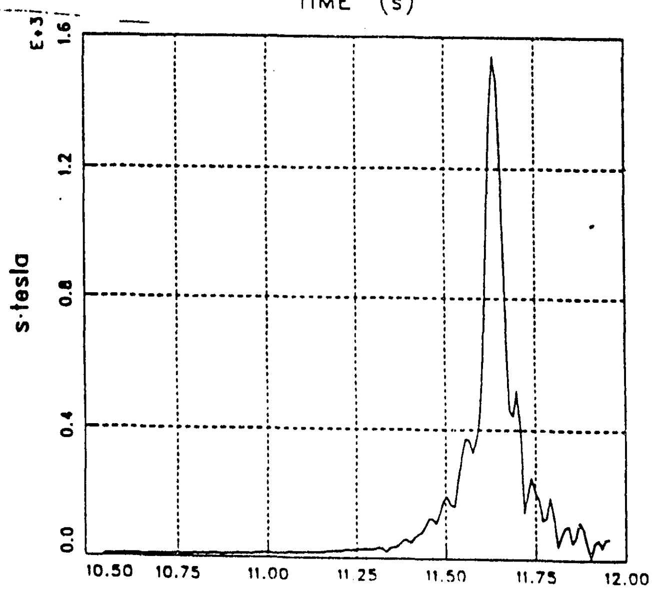
$$B_r(r,z) = \delta B I_1(k_w r) sin(k_w z) \quad , \quad B_z(r,z) = B_0 + \delta B I_0(k_w r) cos(k_w z) \quad ;$$

where $B_0 = 3kG$, $\delta B = 1.8kG$, $L = 2.1cm$ and $k_w = 2\pi/L$. The radius of the pipe is $R = 1.01cm$ and $1kW$ of power is injected at 11.62 GHz . The energy of the injected electrons is $250keV$ and the average current is $400A$. Thus the average efficiency is roughly 10%. For a pre-bunched beam (simulating a two stage device) the efficiency is more than 25%, and we expect by tapering the wiggler to increase the efficiency.

Passive and Active Quasi-Periodic Structures: Both the macro-particle approach and the unified study of an amplifier or oscillator assume uniform slow wave structures. The way the power is injected in or extracted from the structure can become crucial in high power sources. One can view a narrow band structure as a set of coupled cavities. Therefore the coupling of power into the structure has to be addressed in a similar way to the coupling into a cavity. As in a klystron, if the injected power is not sufficient the efficiency is very low. The extraction region is even more important because one has to extract high power levels without affecting significantly the frequency spectrum and with minimum reflections. For this reason we initiated a study of the beam-wave interaction in quasi-periodic structures. These include structures of several cells of periodic structure with one or two transition regions. At this stage we can report


E-3
10.0
0.0
0.0
0.4


E+9
0.3
0.2
0.1
0.0
-0.1
-0.2
watts
0.0
10.0
20.0
30.0
40.0
50.0
E-9
TIME (s)


E+3
1.6
1.2
0.8
0.4
0.0
s·tesla
10.50
10.75
11.00
11.25
11.50
11.75
12.00

results only from the analysis of a passive structure (no beam). We consider a set of coupled cavities of various external radius and length but all with the same internal radius. The coupling - which is determined by the length of the drift tube - between any two cavities can be also arbitrary. Power is coupled in and out with radial arms. The first step in the investigation is to determine the optimal location of the arms. Fig. 7 illustrates the geometry of the narrow band structure with 9 cavities and two arms. In the first case the arms are $6mm$ from the first and last cells and we observe that the average transmission coefficient is $-20dB$. When the drift region was shortened to $1mm$ the transmission coefficient has increases dramatically to an average value of $-3dB$. By small variations in the parameters one can control the frequency at which the transmission is $0dB$. If in the design process we ensure that the phase is advanced by 120^o per cell then, if at the required frequency the transmission coefficient is a minimum, it is easy to add (or remove) one or two cells to obtain a maximum in the transmission coefficient.

Let us now assume for a moment that we have matched the cold system. We know that in the narrow band structure very high gradients develop in the interaction process. In order to avoid rf breakdown we want to increase the volume where the electromagnetic energy is stored and by that we lower the energy density and consequently the field. We started with a "linear" tapering of the external radius of the cavities. We have looked for a range of parameters to bring the transmission coefficient to $0dB$ at one frequency. With no particular design the best we could achieve was $-6dB$ which is not acceptable. At this stage we made an auxiliary analysis of a simplified system (based on transmission line approximation) and one of the main conclusions was that the resonance frequency of each cavity should be kept close to that of the cavities in the uniform structure. Based on this conclusion, we doubled the external radius of the last two cavities. After some fine tuning we were obtained a transmission which is optimized at the required frequency.

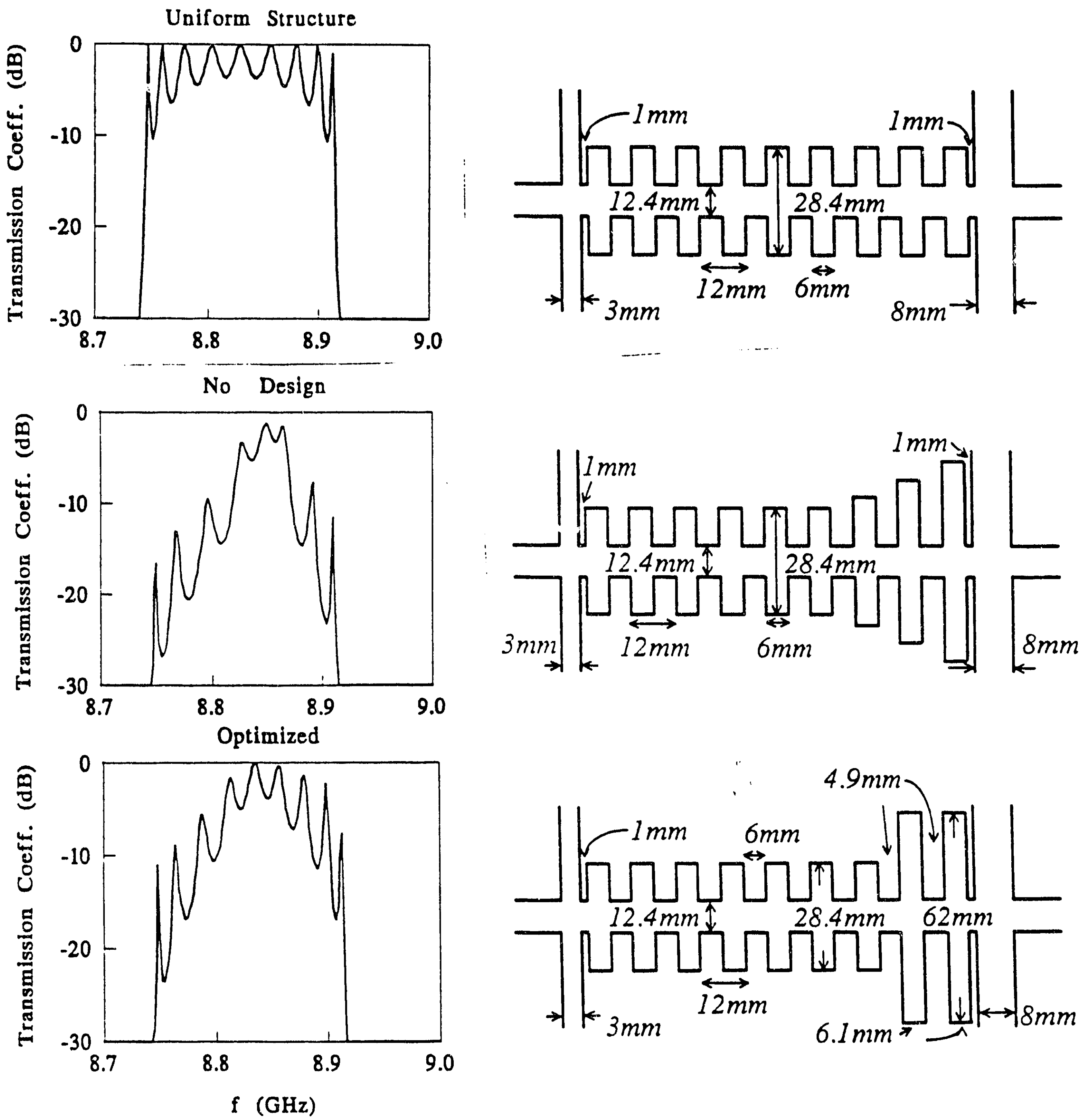
Summary

(1) We believe to have a good understanding of the interaction in a uniform slow wave structure.

(2) Both the experimental and theoretical results indicate that we are able to eliminate the sidebands problem.

(3) In the near future we intend to direct our main theoretical efforts towards the investigation of quasi-periodic structures. We believe that understanding of the reflection and interaction processes ~~there~~ is crucial for the design of effective converters of kinetic energy into radiation. This activity will also be the subject of further experimental effort. The experiments will also emphasize power measurements, confirmation of the elimination of sidebands, and a systematic study of the fluctuation in the far field radiation patterns.

(4) We anticipate that proper design of a converter will eliminate the phase fluctuations in the output signal. We believe that this is a result of beating of the space charge mode with the electromagnetic mode in the output region (see item 3 above).


Uniform Structure
Transmission Coeff. (dB)
0
-10
-20
-30
8.7
8.8
8.9
9.0
1mm
1mm
12.4mm
28.4mm
12mm
6mm
3mm
8mm
No Design
Transmission Coeff. (dB)
0
-10
-20
-30
8.7
8.8
8.9
9.0
1mm
1mm
12.4mm
28.4mm
3mm
12mm
6mm
8mm
Optimized
Transmission Coeff. (dB)
0
-10
-20
-30
8.7
8.8
8.9
9.0
f (GHz)
4.9mm
1mm
6mm
12.4mm
28.4mm
62mm
12mm
3mm
6.1mm
8mm

(5) Alternative sources of radiation will be investigated as part of a continuing effort to develop high power microwave radiation sources. Initially the emphasis will be on theoretical study of the "longitudinal" FEL.

(6) The investigation of ferro-electric ceramics will be continued. This effort includes a study of the rf emission characteristics of ferroelectrics in cavities excited at 2.45 GHz.

(7) A significant effort will be devoted to the development of a repetitive pulser as described in the report. The source will start with operation at the 100 kV level and will be upgarded as we gain operational experience with the system. The beam will be generated from a ferroelectric cathode.

Conference and Journal Articles

Refereed Journal Papers

1. "Electron beam diodes using ferroelectric cathodes," J.D. Ivers, L. Schachter, J. A. Nation, G.S. Kerslick, and R. Advani, Accepted for publication in the Journal of Applied Physics, March 1993/hb

2. "The analysid of a diode with a ferroelectric cathode," L. Schachter, J.D. Ivers, J. A. Nation, and G.S. Kerslick, Submitted to Journal of Applied Physics 1992

3. Slow wave amplifiers and oscillators: a unified study," L. Schachter and J. A. Nation, Phys Rev. A 45,12, 8820, 1992.

Conference Papers

1. "An electron injector based on a high power X band TWT amplifier," L. Schachter, J. A. Nation, G.S. Kerslick, and J. D. Ivers, Port Jefferson Conference Proceedings, 1992.

2. "Narrow pass band high power TWT," L. Schachter and J. A. Nation, Port Jefferson Conference Proceedings, 1992.

3. "The study of a diode with a ferroelectric cathode," L. Schachter, J. A. Nation, G.S. Kerslick, and J. D. Ivers, Port Jefferson Conference Proceedings, 1992.

END

DATE FILMED

7/19/93