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MICROWAVE AND ACCELERATOR RESEARCH

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Introduction

This report describes work carried out on DOE grant number DE-FG02-92ER40731 during the period January 1 1993 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

Experimental Studies

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 described is an extension of DOE sponsored research reported earlier.

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 in the frequency regime centered on 9.0 GHz using a traveling wave tube amplifier (The frequency was dictated by the availability of a magnetron and not by other considerations). In early experiments we reported peak powers of up to 400 MW in a pulse of 90 nsec duration and 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 and to obtain a more constant power output. The origin of the sidebands was 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.

We have adopted a two prong approach to solve this problem. In the first approach we used a severed two stage amplifier. The beam is weakly bunched in the first stage and then injected through the sever into a very low group velocity structure. The importance of the preferred coupled cavity wavenumbers should be significantly less in these devices as the input is transit time isolated from the output. Consequently the cavity does not get a chance to establish preferred values of the wavenumber and the sideband growth is inhibited. We note that we have simulated these new structures using the MAGIC code. Experiment, and results from the simulations confirm that the new structure will eliminate the sidebands. This work has been published in Physical Review Letters during the current year and an extended version of the letter has been submitted for publication in a special issue of the IEEE Trans. Plasma Physics devoted to high power

microwave sources. The transit time isolated amplifier approach successfully eliminates the sideband problem but it seems unlikely that the solution can be extended to work satisfactorily with the $\sim 1.5\mu\text{sec}$ pulse durations now being called for by the NLCTA. Specifically, the low group velocity structures have a very high shunt impedance and hence the electric field at the amplifier walls may be unrealistically high for long pulse duration systems.

The second approach which is currently under active investigation uses a resistive isolation of the amplifier input from its output. The isolation is achieved by the use of silicon carbide loading of the outermost regions of the traveling wave tube structure to strongly attenuate the transmission through the structure in the absence of the beam. Coupling between adjacent cavities is achieved almost exclusively through the bunched beam. Using this approach we have been able to reduce the shunt impedance while maintaining rf attenuation almost continuously along the amplifier length. Results of simulation runs (Figs 1-4) illustrate the difference in performance of two amplifiers one with and the other without resistive isolation. The amplifiers are identical in design with the exception that a thin sheet of resistive material loads the outermost cells of the structure. In fig 1 we compare the wave attenuation of the axial electric field with the absorber present (on the left of the figure) with that in the absence of the attenuator on the right. These results are obtained in the absence of the electron beam. In figure 2 we show the evolution of the axial electron momentum in transport of the beam through the amplifier. The upper figures illustrate the no-loading case. Note that the backstreaming electrons have been eliminated from the experiment in the presence of the resistive loading. This is also manifested by the much better confinement of the beam shown on the right hand side of both figures. In figures 3 and 4 we show comparison plots of the time evolution of the wave axial electric field at the end of the amplifier and the Poynting flux through the output of the structure. Note the steady behavior of the field and power in time for the resistively loaded case in the lower part of the figures. In fact, as seen in the upper part of figure 3, the undamped system does not reach an equilibrium during the 20 nsec. of the simulation. Note also in figure 4 that the FFT of the output radiation exhibits sidebands in the absence of the damping but that the wall loaded case shows only the required single frequency. The axial electric field at the beam location in the damped TWT amplifier is restricted to about 20 MV/m - nearly one order of magnitude lower than that obtained in the transit time isolated amplifier described earlier.

In these runs we are only extracting about 25 MW from the beam at 6 % power conversion efficiency and we absorb about 100 MW in the resistive loading. Clearly this is not an acceptable division. In practice we plan to test the stabilization concept with thin films of Silicon Carbide mounted in the outermost regions of the amplifier cavities and to subsequently replace the resistive loading with output coupling ports so that the 'dissipated' power can be usefully extracted as rf power.

We have fabricated an amplifier to test these ideas and satisfactorily cold tested the design. We plan to carry out beam loaded tests of the structure early in the new year.

MAGIC VERSION APRIL 1993 DATE Oct 8 1993
SIMULATION Venus.120c.6S/m,cold upper 0.7mm

PLOT AT TIME1.50E-08 SEC
E1 COMPONENT
RANGING FROM (2.2) TO (394.2)

MAGIC VERSION APRIL 1993 DATE Oct 8 1993
SIMULATION Venus.120c.0.0003S/m,coldenergy con lb

PLOT AT TIME2.00E-08 SEC
E1 COMPONENT
RANGING FROM (2.2) TO (394.2)

Fig 1

MAGIC VERSION APRIL 1993 DATE Oct 8 1993
SIMULATION Venus.121,500A,lossless,25kvlookb

TIME HISTORY PLOT 12
E/M FIELD ENERGY

MAGIC VERSION APRIL 1993 DATE Oct 8 1993
SIMULATION Venus.121,500A,lossless,25kvlookb

TIME HISTORY PLOT 24
E1 COMPONENT
AT COORDINATE (318.2)

MAGIC VERSION APRIL 1993 DATE Oct 7 1993
SIMULATION Venus.120,500A,6S/m,25kvenergy con lb

TIME HISTORY PLOT 12
E/M FIELD ENERGY

MAGIC VERSION APRIL 1993 DATE Oct 7 1993
SIMULATION Venus.120,500A,6S/m,25kvenergy con lb

TIME HISTORY PLOT 24
E1 COMPONENT
AT COORDINATE (318.2)

MAGIC VERSION APRIL 1993 DATE Oct 8 1993
SIMULATION Venus.121.500A,lossless,25kvlookb

TIME HISTORY PLOT 6
MAGNITUDE OF FFT OF TOTAL POYNTING FLUX

MAGIC VERSION APRIL 1993 DATE Oct 8 1993
SIMULATION Venus.121.500A,lossless,25kvlookb

TIME HISTORY PLOT 6
TOTAL POYNTING FLUX

MAGIC VERSION APRIL 1993 DATE Oct 7 1993
SIMULATION Venus.120.500A,65/m,25kvenergy con lb

TIME HISTORY PLOT 6
MAGNITUDE OF FFT OF TOTAL POYNTING FLUX

MAGIC VERSION APRIL 1993 DATE Oct 7 1993
SIMULATION Venus.120.500A,65/m,25kvenergy con lb

TIME HISTORY PLOT 6
TOTAL POYNTING FLUX

In this experiment we have designed and utilized a single side arm input coupler to input rf into the amplifier. Our initial tests will extract the amplified signal along the axis of the system, as we have done previously. Theoretical and experimental work has also been carried out on the design of output ports from the last cavities of the amplifier. Some discussion of the theoretical aspects of this study will be presented in the theoretical section of this report. We also note that simulation and experimental work has been carried out on the design of transitions between slow wave structures. The main result which has emerged to date is the observation that a single step transition (i.e. a single period of the rippled wall amplifier with different dimensions to that of the main amplifier) gives a better impedance match than can be obtained with an adiabatic taper. Possibly the single step transition behaves more like a quarter wave transformer.

Repetitive Source Development: We have extended our effort which was initiated last year to obtain a compact low repetition rate modulator to drive electron beams for microwave generation experiments. The approach used has been modified substantially with the ferrite bead loaded cable transformer replaced by a large diameter ferrite core transformer system driven by four 18 Ohm pulse lines. The system was described at the SLAC NLC workshop in October. The principle features of the system are shown in figs 5 - 7. Each Blumlein driver may be thought of as two pulse lines arranged with opposite polarity charging. The switch is then located at the load isolating the positive charged lead from its negative counterpart. The line schematic is shown in figure 5 together with a SPICE simulation output of the modulator into a matched resistive load. For the purpose of comparison an conventional Blumlein with identical components (other than the charging polarities and the switch location) is shown in fig 6. Note that the pulse shape and rise time is much better with the new arrangement. The switch location at the load eliminates the oscillations due to the line itself and the rise time improvement occurs since the transfer function of the finite length line cannot degrade the leading edge of the pulse. The plus/minus charging of the system could be replaced by two lines both charged to 40 kV but with one line going from 0 to 40 kV and the second from 40 to 80 kV. This would allow the use of a single thyatron-switch instead of two 40 kV switches with one floated. The transformer assembly uses a 9:1 step up for each line as shown in figure 7. Each pair of primary Blumleins feeds 5 ferrite cores and the secondary links all ten cores. This arrangement allows the outputs to add algebraically giving an effective 18:1 step up but with the rise time characteristics of a 9:1 transformer.

A transformer of this type has been built and two photographs of the assembly are shown in figure 8. We are in the process of commissioning the transformer and have carried out the first low voltage tests. In figure 9 we show a trace of the low voltage output of a 6:1 single stage prototype of the transformer. The result of the change to the plus-minus charging system is clearly evident in the excellent ~ 75 nsec rise time of the output into a dummy load. The first shots, taken at about ~ 150 kV output voltage, on the two stage by 9:1 step up transformer shown in the pictures indicates a slower rise time ~ 170 nsec than expected. We are currently completing the tests and will modify

Blumlein Model for SPICE

Plus-minus charging

All inductances equal: $L = 300 \text{ nH}$
All capacitances equal: $C = 3.6 \text{ nF}$

Output Voltage from SPICE Model

Blumlein Model for SPICE Single polarity charging

All inductances equal: $L = 300 \text{ nH}$
All capacitances equal: $C = 3.6 \text{ nF}$

Blumlein driven pulse transformer Plus-minus charging

All inductances equal: $L = 300 \text{ nH}$
All capacitances equal: $C = 3.6 \text{ nF}$

Design Parameters:

PFN impedance: 10 ohm
Output voltage: 720 kV
Output current: 500 A

Fig 8

Output Waveform from plus-minus charge line

14 kV/div, 100 ns/div

Blumlein:	10 ohm
Transformer:	6:1
Load:	600 ohm
Charge Voltage:	+/- 5 kV
Output Voltage:	35 kV
Risetime:	75 ns
Cores:	6 (1x6)
Total V-sec:	0.012

Fig 9

the design as needed to improve the output pulse. The system, revised as needed, will be put under oil in the new year and an automatic reset network added to allow operation at about 1 Hz. The output design parameters for the transformer are 720 kV, 500 A, with a pulse duration of 200 nsec and a repetition rate of 1 Hz.

The modulator just described will be used with our recently developed ferroelectric electron sources which will be used as the cathodes for the beam generation. During the last year we have extended our research on ferroelectric cathodes to include operation at 15 to 20 kV. They continue to show promise as electron beam sources for rf generation. A summary of the results obtained in the last year is given below.

Ferroelectric Cathodes: Work has centered during the last year on extending the electron beam duration and on increasing the beam energy. We have also made substantial progress towards obtaining a first measurement of the beam emittance at 14 keV electron beam energy.

Figure 10 shows two photographs of the time variation in the electron beam current for diode gap lengths of 1.5 cm, beam energy of 1 keV, and a load impedance of 50 Ohms. The pulse duration is seen to vary from about 300 nsec in the upper picture to 2 μ sec in the lower picture. The pulse duration matches the length of the applied voltage pulse in both cases and should be noted continues in time well beyond the switching pulse. The upper part of each picture shows the pulse used to switch the ferroelectric and the lower the beam current.

We have also increased the voltage applied to the ferroelectric diode. Figure 11 shows two pictures of the diode current, the upper trace in each case, for a diode voltage of 13.8 kV supplied from an 18 Ω Blumlein identical to the lines used to power the transformer described above. The time τ indicates the delay between the pulsing of the ferroelectric and the voltage applied to the diode gap i.e. the 13.8 kV. The lower trace in each picture shows the applied gap voltage. In both cases the current duration matches the duration of the applied gap voltage. The diode current depends on the delay between the two pulses and is repeatable.

From the above and similar data not reported above we conclude that it is possible to extract long current ($\sim 1\mu$ sec) pulses from a ferroelectric cathode and that the current amplitude can be controlled by the diode gap and by the delay between applying the switching pulse and the diode voltage.

We have also initiated a program to measure the beam emittance using radiochromic film. The beam is injected through an array of thin slits and the film records the beamlet profiles some distance behind the slit array. Data has been obtained in a variety of beam operating conditions and the films have been scanned in a densitometer but the data has not been analyzed yet. Preliminary indications suggest that the emittance may be larger than originally hoped.

Diode Current and Gap Voltage

$I_{\max} = 12\text{A}$, $V_{\text{Anode}} = 1.0\text{kV}$, $Z_L = 50\Omega$, $d = 1.5\text{cm}$, $l_{\text{cable}} = 30\text{m}$.

Diode Current and Gap Voltage

$I_{\max} = 16\text{A}$, $V_{\text{Anode}} = 1.0\text{kV}$, $Z_L = 50\Omega$, $d = 1.5\text{cm}$, $l_{\text{cable}} = 200\text{m}$.

Diode Current and Gap Voltage

$\tau = 450\text{ns}$, $I_{\text{max}} = 20\text{A}$, $V_{\text{pulse}} = 13.8\text{kV}$, $Z_L = 18\Omega$, $d = 5\text{cm}$

Diode Current and Gap Voltage

$\tau = 1100\text{ns}$, $I_{\text{max}} = 40\text{A}$, $V_{\text{pulse}} = 13.8\text{kV}$, $Z_L = 18\Omega$, $d = 5\text{cm}$

Finally we observe that the long pulse duration data suggests that the emission may arise in part from secondary emission from the cathode. This conclusion is reached because the charge density transferred through the diode reaches $40 \mu\text{C}/\text{cm}^2$ a factor of about two greater than the maximum expected polarization charge density. Our current belief is that the pulse applied to the ferroelectric causes field emission. Energetic electrons hit the surface of the gridded cathode and cause additional emission. The measured diode current is probably due to a combination of the two emission processes.

Theoretical Studies:

The theoretical effort toward development of high power microwave (HPM) sources during the period of 1993 covered several topics which are summarized below. More detail on the work can be found in the publications referenced at the end of this report.

Quasi-Periodic Structures: If we examine the difference between a klystron and a traveling wave tube amplifier we realize that a klystron consists of a metallic pipe connecting two or more cavities. The pipe is designed such that at the frequency of interest the electromagnetic wave is below cutoff, and in the absence of the beam the cavities are *isolated* from each other. The beam wave interaction is limited to the close vicinity of the cavities. Since this is typically a small fraction of wavelength the system becomes susceptible to RF breakdown at high power levels (above 50MW at 11.4GHz). This problem is less severe in a disk loaded traveling wave amplifier (TWA) which consists of a series of *coupled* cavities, since the beam-wave interaction is distributed along the entire structure.

The signal in a klystron is carried by the space-charge waves on the electron beam and pure electromagnetic waves can not propagate between adjacent cavities. This is different in a traveling wave tube amplifier since the various cavities are coupled and electromagnetic waves can propagate both parallel and anti-parallel to the beam. The latter can be destructive since they allow undesired feedback which may cause the system to oscillate. Reflections are also the reason for asymmetric sidebands which occurred in the spectrum of two stage amplifier as reported in the past. As described earlier in this report we have designed a structure to eliminate the reflections by making the time it takes the first reflection to reach the input end of the same order of magnitude as the electron pulse length, thus by the time the reflection becomes relevant there are no more electrons to interact with the reflected wave. This method was successfully demonstrated experimentally and power levels of 160MW were achieved at 9GHz. The spectrum of the output signal was less than 50 MHz and the pass-band of the periodic structure was less than 200 MHz. The drawback of the method is associated with the large electric field gradients ($> 200 \text{ MV/m}$) which occur at this power level. Although no RF breakdown was experienced it will be necessary to increase the volume of the last two or three cells in order to minimize the electric field on the metallic surface if we wish to increase the power level or the pulse duration. As a result it is necessary to consider a quasi-periodic system. In the following section we review progress on the study of quasi periodic structures.

The main two problems of an extraction section based on a quasi-periodic disk loaded structure are: (a) minimizing the reflections at both ends of the structure in order to avoid oscillation at high power levels and (b) tapering the output section in order to avoid breakdown and, optionally compensate for the velocity decrease of the electrons. To optimize these two conflicting requirements we developed an analytical technique which enables us to analyze and design a quasi-periodic structure.

The Electromagnetic Problem: The first step was to analyze a system which consists of two symmetric arms on a set of coupled cavities. Two important conclusions were revealed by this analysis namely, (i) the effect of the cavity coupling becomes dominant when the tuning of a non-uniform (tapered) structure is required and, (ii) The location of the arm relative to the adjacent cavities is crucial for efficient injection and extraction of power out of the system. We subsequently examined the radiation intensity from a dipole on the axis of a quasi-periodic structure which consists of 9 cavities and two arms. It has been shown (paper #8 in the list of references) that there is a clear pattern of increased intensity when the dipole is in the gap region of one of the cavities compared to the case when it oscillates in the drift (iris) regions. By increasing the separation between two cavities (say the third and forth) the Green's function of a two stage amplifier may be determined and the trivial result of input-output isolation recovered. The effect of geometry on the radiation intensity of a current distribution, which resembles that in a traveling wave amplifier in the exponential gain regime, was also considered. As in the pure electromagnetic problem there is a clear pattern of coupled cavities and a significant increase in the extracted power can be achieved by optimizing the external radius and hence the resonant frequency of the last cavity.

Hydrodynamic Approximation: In this case we have calculated the gain of a quasi-periodic structure in the framework of a linearized hydrodynamic approximation. Special attention was paid to the space charge modes since, in comparison with the electromagnetic modes, they propagate only along the direction of beam propagation. By varying the geometry of the last cavity and its separation from the previous cavity, we were able to show that the gain can be maximized. Furthermore, the input was isolated from the output to simulate a klystron with a traveling wave structure at the output and a significant increase in the gain was found.

Asymmetric Output: The Green's function calculation indicated above assumed symmetric input and output arms. Although some important features were identified a more realistic model is required for an experiment since a system is typically fed by a rectangular waveguide so that it is no longer azimuthally symmetric. In order to account for this asymmetry the output arm was replaced with a radial open "horn" and a short circuited "horn" to model a stub tuner. The calculation was performed for a current density which resembles the spatial distribution of the current density in a traveling wave amplifier. The gain is defined as the ratio of the power emitted by this current distribution when in the structure compared to that in free space. Obviously the stub tunes the system but it should be noted that the *maximum gain does not occur for minimum reflection* from the surface of the last cavity (between the arm and the stub tuner there is a reflecting metallic surface). We checked the variation of the

maximum gain as a function of the external radius of the last cavity and practically no change was found. It should be mentioned that for each value of the external radius the stub geometry has to be changed to obtain maximum gain. The angular span of the stub or arm and their relative angle have little effect on the maximum gain. The detail calculation was submitted to IEEE Transactions on MTT, reference #9 in this report. This work was performed at Ben Gurion University (BGU) in Israel.

Transit Time Isolation of a TWA

Although the "transit time isolation" accomplished our main goal, namely the elimination of sidebands from the spectrum of a high power traveling wave amplifier, there is one analytic problem which remains to be resolved. Both the analytic simulations and MAGIC code results predict a very high gain per cell in the narrow band structure, significantly higher than the resulting 160MW observed would indicate. We attribute this discrepancy to the effect of the sever. We know that the sever attenuates (-25dB) the electromagnetic mode but we do not know its effect on the space charge modes. In order to examine this qualitatively we have used the 1D code described in previous reports. For modeling we have used a 30cm long dielectric amplifier operated at 8.88GHz and driven by a 1kA, 1MV, 0.3cm radius pencil beam. The interaction impedance for this structure is calculated and found to be $0.4k\Omega$. Using these parameters we compute the gain of this first stage to be approximately 27dB. We know that it is the slow space charge wave which is actually amplified in the interaction process. The sever attenuates only the electromagnetic wave and so we assume it has no significant effect on the *amplitude* of the space charge wave. However the phase, relative to the beam bunching, depends critically on the sever length. We therefore use the code to examine the effect on the gain of changes in the wave phase in transit through the sever. Note that for space charge wave propagation along a strong axial magnetic field in free space or in a pipe the current density is orthogonal (90°) in phase to the longitudinal electric field, whereas in a traveling wave structure the slow space-charge wave has a complex wavenumber and the relative phase is approximately 120° . The phase between these two quantities is very important since it is the scalar product of the electric field and the current density which controls the energy exchange.

In the simulation the narrow band structure was assumed to be 12cm long with a calculated interaction impedance of $5k\Omega$. The particle distribution on both sides of the transition point (the sever is modeled with zero width) was assumed to be identical as was the wave amplitude. However, the phase of the field is shifted. For an input power of 25kW the power can vary from 190MW to a few MW's as the phase was shifted from 300° to 150° . We conclude that the sever can affect the relative phase between the current density and the longitudinal E-field. Its effect should be carefully considered, not only for electromagnetic isolation of the input from the output, but also to optimize its influence on the space charge mode(s). We intend to consider this topic in a more systematic manner during the summer of 1994.

Periodic Permanent Magnets: The cost of generation of high power microwaves for

particle acceleration may be reduced significantly by the use of a permanent periodic magnetic (PPM) field to guide the beam. On axis this field can be described by $B_z = B_0 \cos(2\pi z/L)$ where L is the period. We have initiated an investigation of this option and have explored the envelope equation for the beam with the self fields of the beam included, and for axially symmetric laminar-flow. The envelope equation has been solved numerically for the parameters of interest in our lab. In the linear region, the optimal condition to confine the beam is the same as that in Brillouin flow provided that the rms value of the periodic magnetic field is identical to that of the uniform field in the Brillouin flow. For practical cases we numerically calculate the radial excursions of the beam as a function of the radial velocity of the outermost electrons on entry into the ppm region. For a period length of the ppm of 3.2 cm and an axial field strength of field is 2.7 kG, which satisfies the Brillouin condition for a beam radius 3 mm we find that the system is very sensitive to radial motion of the electrons. Preliminary indications suggest that control of the transverse momentum of the electrons on injection into the ppm focusing region will be critical.

TM-FEL: An interesting option first described in our last annual report is to consider the beam interaction with a TM wave in the presence of a wiggler as determined by the PPM in a *uniform* pipe. The absence of edges in this case lowers the probability of breakdown. Within the framework of the macro-particle approach it has been shown that this interaction is almost identical to that of a TWA rather than of an FEL. Therefore we have the advantages of the FEL (uniform wall) without its main disadvantage namely sensitivity to beam quality. It is planned to include the effect of the TE modes in this calculation during the summer 1994 period.

New Directions in RF Sources. At the IEEE/APS Particle Accelerator Meeting (May 1993, Washington DC) we presented a review on new directions in RF sources for particle accelerators. In this work we classified the various sources according to several criteria:

- (i) acceleration scheme (conventional or two beam accelerator) and,
- (ii) approach followed to overcome the breakdown problem namely, increase the frequency (CERN), pulse compress (SLAC) and thirdly TW structures, (SLAC, Cornell and Haimson/LLNL). The distributed interaction in the case of the TW structures leads us to the interaction type: here we distinguish between slow wave devices (Cerenkov) and fast wave devices (FEL, CARM, Gyrotron etc..).

The main conclusions were that there is a significant advantage operating at the highest frequency permitted by the alignment and wake field constraint and that at high power levels the local beam wave interaction occurring in a klystron is disadvantageous compared to distributed interaction found, for example, in a TWA due to the breakdown problem. The high efficiency and breakdown constraints imply that a twistron (a klystron with a TW output section) are of special interest and, in particular, the design of the output section with one or more arms is critical.

Proposed Work: During the coming year we propose to continue our work on high

power microwave generation and on ferroelectric cathodes. The work will focus on the following topics:

1. Obtaining a steady output in time from our TWT amplifiers. The approach to be investigated will concentrate on resistive isolation of the input from the output of the amplifier as described in the body of the text.
2. Develop a sidearm output coupler to handle high power rf signals in X band. This work will be both theoretical and experimental.
3. Completion of our new 1 Hz pulser and its integration into a beam facility. Depending on the time scale of completion of the facility we will initiate work on the use of the facility in high power microwave source development.
4. We shall extend our initial investigations into ppm focusing systems including the theoretical analysis of amplifier performance in a ppm transport system. This activity will also be explored experimentally if time and funds permit.
5. We shall extend the theoretical analysis of electron beam wave growth in TWT structures to quasi periodic structures using the macro-particle approach previously used in periodic structures. Part of the formulation will be done at BGU by Levi. Schächter and it will be continued and hopefully completed at Cornell University during the summer. This will result in the development and construction of an output section for our TWT's.
- 6 We shall extend the theoretical studies in progress on the FEL concept outlined in this and last years annual report.
7. We shall complete our ferroelectric cathode emittance study and will incorporate a ferroelectric cathode in our low repetition rate system.
8. We shall complete a parametric investigation of the ferroelectric diode scaling characteristics at voltages in the 20 kV range. This will be an integral part of the gun design outlined in item 7.

Conference and Journal Articles

The following papers have been published or submitted for publication during the last year.

Refereed Journal Papers:

1. J.D. Ivers, L. Schächter, J.A. Nation, G.S. Kerslick and R. Advani; Electron Beam Using Ferroelectric Cathodes. J. Appl. Phys. 73(6) 2667-2671(1993).
2. L. Schächter, J.D. Ivers, J.A. Nation and G.S. Kerslick; The Analysis of a Diode with a Ferroelectric Cathode. J. Appl. Phys. 73(12) 8097-8110(1993).
3. T.J. Davis, L. Schächter and J.A. Nation; High Power Microwaves at 9GHz from an Extended Length Cavity in a Coaxial Beam Geometry. Appl. Phys. Lett. 63(13) 1854-6 (1993).
4. E. Kuang, T. J. Davis, G. S. Kerslick, J.A. Nation and L. Schächter; Transit Time Isolation of a High Power Microwave Amplifier TWT. Phys. Rev. Lett. 71(16) 2666 (1993) .

5. L. Schächter and J.A. Nation; An Analytical Method for Studying Quasiperiodic Disk Loaded Waveguide. Appl. Phys. Lett. 63(17),1-3 (1993).
6. T.J. Davis, L. Schächter and J.A. Nation; Results from an X-Band Coaxial Extended Length Cavity. Submitted for publication to IEEE - Trans Plasma Science (Special Issue on High Power Microwave).
7. E. Kuang, T.J. Davis, G.S. Kerslick, J.A. Nation and L. Schächter; Low Group Velocity Traveling Wave Tube Amplifier. To be published in IEEE - Trans on Plasma Science (Special Issue on High Power Microwave).
8. L. Schächter and J.A. Nation; An Analytical Approach for Analysis and Design of Quasiperiodic Structure for High Power Microwave Sources. Submitted to J. Appl. Phys.
9. L. Schächter; On the Coupling Between a Quasiperiodic Structure and an Asymmetric Output Arm, submitted to IEEE Transactions on Microwave Theory and Techniques.

Conference Papers:

1. L. Schächter, New Directions in RF Sources. Presented at the IEEE/APS Particle Accelerator Conference 17-20 May 1993 Washington DC.
2. L. Schächter, T.J. Davis and J. A. Nation; TM-FEL with Longitudinal Wiggler and an Annular Beam. IEEE-APS Particles Accelerators Meeting PAC'93 Washington DC, May 15-20 1993.
3. L. Schächter and J.A. Nation; Beam-Wave Interaction in Quasiperiodic Structures. IEEE-APS Particles Accelerators Meeting PAC'93 Washington DC, May 15-20 1993.
4. E. Kuang, G. S. Kerslick, J. D. Ivers, L. Schächter and J. A. Nation, Development of high power X-band TWTS, Presented at the 20th IEEE International Conference on Plasma Science, 7-9 June 1993, Vancouver, B.C., Canada.
5. Development of high power X-band TWTS," Repetitive electron beam source for high power microwave experiments, Presented at the 20th IEEE International Conference on Plasma Science, 7-9 June 1993, Vancouver, B.C., Canada.
6. J. D. Ivers, G. S. Kerslick, J. A. Nation and L. Schächter, A compact, low cost modulator for rf sources, Presented at IEEE Particle Accelerator Conference, Washington DC, May 17-20, 1993.