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Table of Contents.

Introduction.....	1
Technical program.....	1
Experimental Program.....	2
Theoretical Program.....	5
Conclusions.....	7
Publications.....	8
Journal Articles.....	8
Conference Presentations.....	11
Appendices.....	14
1. Symmetric and Asymmetric Mode Interaction in High-Power Traveling Wave Amplifiers: Experiments and Theory.	
2. High Power Microwave Generation Using A Ferroelectric Cathode Electron Gun.	
3. Notes on Performance of a Two-Stage 35 GHz, Ka Band Amplifier.	

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Introduction.

This report describes research carried out on DOE Contract DE-FGO2-92ER40731 during the period June 1, 1992 – May 31, 2000. A six month no cost extension was granted for completion of work following the contract termination. The funding available ran out on June 15th 2000 when work, with the exception of the preparation of this report and Journal publications, ceased.

The report summarises the main technical objectives and accomplishments during the life of the grant and concludes with data on publications describing the research. Details of the results obtained may be found in the publications listed. Copies of two papers are appended to this report. The first, which has been accepted for publication describes the completion of our work on X-Band amplifiers, and the second, which is under review for publication, describes the final development of our ferroelectric gun and demonstrates its use in a simple X-Band amplifier. A third appendix summarizes preliminary data obtained on a Ka band amplifier at 35 GHz. This device demonstrated gain and shows persuasive evidence that a TWT amplifier may be a serious candidate for use in a collider operating at ~35 GHz.

Technical Program.

The technical program had experimental and theoretical components which will be summarized separately. In both cases the main activity was the development of very high power microwave sources, initially in X-band, and recently initial work on a Ka band TWT amplifier. There was an additional activity started in 1991, under a previous DOE contract, on ferroelectric emitters.

Highlights of the program include:

1. The development of a relatively broad band microwave source yielding ~75 MW power at a power efficiency of 54% and an energy conversion efficiency of 43%. The energy conversion was limited by the pulse power rise time and it is expected that, with a longer voltage pulse would have matched the power conversion efficiency. Operation of the modulator at 800 kV, instead of the usual 700 kV, lead to peak power generation of 120 MW.
2. The development of a ferroelectric cathode electron gun which yielded a beam current of up to 350 A at 500 kV. The device was shown to operate satisfactorily at a low repetition rate, limited by the available power supplies. The extent of this achievement must be measured against the state of the art when the program started in 1991 and diode currents of a few amps at a few hundred volts had been achieved. The final beam power obtained exceeds that achieved elsewhere by several orders of magnitude. Furthermore the gun development achieved in the last year of this research was shown to give an electron beam suitable for high power X-band microwave sources with the demonstration of a 5 MW tuneable X-band TWT single stage amplifier.

3. In the final year and a half of the program work was initiated on a Ka-Band TWT amplifier. Gains of over 30 dB were achieved at peak output powers of about 4 MW. This work unfortunately was incomplete at the termination of the program.

Experimental Program

Microwave Generation: The experimental program was focussed on the generation of high power microwave radiation, initially in X band and more recently in Ka band. The latter work was based on a direct extension of the X-band device. The primary pulse power source for the TWT investigated was a 700 kV, ~200 A, 80 ns. relativistic electron beam. All of the experiments were carried out in single shot mode, i.e. repetitive source operation was not possible with this modulator.

Full details of the operation of the X-band device are provided in the appended paper, which has been accepted for publication in the IEEE Transactions on Plasma Science. We will, in this report, only focus on the key issues for successful operation and leave the details to the Journal paper.

The X-band source investigation has been in progress over several years and only reached fruition a little over one year ago. The amplifier used consisted of two sections, separated from each other by a SiC sever. The first section was a dielectric amplifier which served to buffer the main amplifier from the input microwave source. The gain of this amplifier was small ~10 dB or less so that the power level at the end of the dielectric section was typically in the range 10-500 kW. Its primary purpose was to provide an initial bunching of the electron beam and to isolate the input microwave coupler from reflections in the second stage. This was accomplished by use of a sever which attenuated any X-band microwave signal by about 25 dB. Following the sever we employed an inhomogeneous disk loaded amplifier having two parts. The input and the output of the amplifier employed ten or twelve cell tapers to reduce reflections. The first part of the amplifier used a long section in which the cold wave phase velocity exceeded the speed of light by a few percent. It has been shown that operation in such a device leads to an efficient bunching of the electron beam. Immediately following the buncher section we used a short (4 cell) transition to the output section in which the cold wave phase velocity was about 0.78 c. The low phase velocity enhanced the conversion of beam energy into microwave radiation.

A key feature of the device was the use of a low reflection coefficient transition from the disk loaded amplifier to a cylindrical coaxial tube in which the radiation propagation was in a TEM mode. The junction efficiently converted the TM mode in the disk loaded amplifier to the TEM mode in the output. The low reflection coefficient of the mode converter extended over a bandwidth of several hundred MegaHertz allowing an instantaneous bandwidth for the amplifier of about 500 MHz, centered on 9 GHz. In addition it served to decouple the radiation from the beam electrons. This is important from the efficiency point of view, since the electromagnetic wave speeds up in the output taper and recouples the electromagnetic energy into kinetic energy of the electrons. Finally we note that successful operation of the amplifier at high efficiency required the

use of severs and microwave absorbers to reduce the amplitude of any unwanted reflected wave. It is important to note that reflections may occur at preferred frequencies not equal to the amplified wave frequency so that the absorbers must be broad band. With the use of these precautions we found it was possible to generate 75 MW at 54% efficiency and up to 120 MW with a higher (800 keV) energy electron beam.

In earlier work we found that the electron beam drifted off the amplifier tube axis with a loss of beam to the walls. This effect limited the output power. After extensive study we identified the source of the beam loss as an angular error in the beam pipe of about 0.5 degrees. This occurred at a flange joining two sections of the pipe. As a result of the beam loss and before the alignment error was finally identified, we initiated a detailed theoretical and experimental investigation of the growth of HEM modes in the amplifier. These are asymmetric modes and lead to the BBU instability in electron beams. Details of these studies are also presented in the appended paper. For the purposes of this summary we found that the HEM modes were not important in the amplifier operation, even when the expected HEM interaction frequency was close to amplified wave frequency. This unexpected result allows for broadband operation of the amplifier in relatively oversized waveguides and allows operation of similarly designed amplifiers at higher frequencies. Specifically, we carried out preliminary studies of a TWT amplifier operating in Ka-band at a frequency of 35 GHz. A report on this work was presented at the AAC conference in Santa Fe in July 2000. In these studies we carried out an initial investigation of a dielectric amplifier driven by an 850 kV electron beam. We achieved amplification at 35 GHz with an output power of up to 2 MW with a 5 kW input signal. This work was continued with the development of a single stage disk loaded amplifier the design of which was based on our successful X-band work. Similar results to those obtained with the dielectric amplifier had been achieved by the conclusion of the contract. Although the investigation was incomplete and rf conversion efficiency was only about 2%, we believe that system efficiencies of 40% are available at the higher frequency with further development of a two stage device. This observation is based on MAGIC simulations, which were in good agreement with experiment at X-band, the insensitivity of the TWT amplifier to the HEM mode, and our experiences with the lower frequency operation.

In summary we have demonstrated efficient operation of a TWT in X-band at power levels useful for the NLC class of accelerators. Preliminary work also suggests that it will be possible to build similar devices with up to 40% efficiency at 35 GHz. It has also been demonstrated that the HEM modes do not appear to be important in the TWT's studied.

Ferroelectric Cathodes and Electron Beam Generation: As in the case of our X-Band amplifier summary we have chosen to append an article recently submitted for publication to detail our recent work in this area. In what follows we only summarize key features of the work. It should be noted that the performance achieved by the end of the contract exceeded by far the performance of any other ferroelectric emitter, and in fact demonstrates that these devices should be further investigated for use in high power microwave applications.

We have, during the course of this research taken the development of a ferroelectric cathode from its earliest demonstration at the Ampere emission level to the development and first application of a two stage electron gun capable of producing a 350 A beam at 500 kV in a 350 ns pulse. The gun used a planar cathode which was recessed into the cathode surface to provide electrostatic beam focussing. The final compression was obtained using a converging solenoidal magnetic field. The magnetic field profile and the gun design were based on computer designs using the EGUN and the MAGIC codes.

Experimental Results: The gun performed as expected from the simulations. The beam current density was up to 37 A/cm^2 . The ripple on the beam surface was reduced to 0.3 mm and could have been made even less with a more careful match of the experimental configuration and the simulation design. We have demonstrated the suitability of this source for High Power Microwave generation by showing successful operation of a single stage TWT amplifier at ~ 9 GHz with output powers of several megawatts. Operation was at a low repetition rate of 0.1 Hz.

Our original objective was to measure the beam emittance to show that it was sufficiently low to permit microwave amplifier operation. We have in effect reversed this process by demonstrating amplifier operation and hence inferring that the emittance is low enough to be useful. In these experiments the beam current was about 100 A and the gun voltage 450 kV. As illustrated in the appended article we obtained an output power which peaked at about 9.4 GHz at a power level of approximately 6 MW. The peak power level was limited by the use of a single stage amplifier and by the relatively limited efforts made to minimize reflections from both ends of the amplifier. The maximum gain available was about 30 dB and the measured instantaneous 3 dB bandwidth approximately 400 MHz.

We have attempted to place an upper bound on the beam emittance by comparing the microwave gain observed with that predicted by the PIC code MAGIC. With the use of the actual experimental geometry, and the beam and microwave inputs equal to those used in the experiment, we have determined that the simulated microwave gain is insensitive to the beam emittance. From these observations we can only say that the emittance is less than $400 \pi \text{ mm.mrads.}$, under amplifier operating conditions. We have, in addition, carried out a set of measurements in order to make an initial direct measurement of the beam emittance. This relies on the concept that a pencil beam will retain, in zero order, its emittance as the beam diameter is increased or decreased due to adiabatic changes in the beam size as a result of variations in the strength of a solenoidal

confining magnetic field. We use an adiabatic beam expansion to reduce space charge effects and allow an estimate of the beam emittance. The beam was expanded from its equilibrium radius to about 10 mm in radius as the axial magnetic field was dropped to a value of a few hundred Gauss. The emittance was estimated using a 7 slit mask with each slit having a 0.35 mm width. The beamlets were detected 4 cm behind the mask using radio-chromic film and yielded an estimated emittance of 10π mm. mrad. Although this value is considerably different to that found in our earlier estimate the two results are not inconsistent due to the extreme insensitivity of the microwave amplifier to the beam emittance.

In conclusion we point out that we have developed a ferroelectric cathode electron gun for use in HPM research. The design meets the requirements of the program for beam generation in an X band amplifier as was directly demonstrated experimentally.

Ka-Band TWT Amplifier: We have worked in the last contract period on extending our X-Band amplifier operation to Ka-Band at 35 GHz. We append detailed notes on our development of this device. In this section we simply note that the results are preliminary but encouraging. We achieved amplifications in excess of 30 dB with output powers of several Mega-Watts. Further work is still required to confirm these power levels and to extend the operation to the high efficiencies predicted by the PIC code analysis.

Theoretical Program

In the latter part of this program we focussed on analysis in 1 and 3 Dimensions of the growth and competition between HEM and TM mode operation of the TWT. Details are provided in published papers and are summarized below.

1D MODEL: We developed a model that enables one to determine the coupling between the HEM and the TM_{01} modes. When such a (linear) coupling occurs there are two other modes that are a linear superposition of the previous mentioned mode. We shall refer to these new eigen-modes as "TM₀₁-like" and "HEM-like" modes since at the limit of no coupling they correspond to the TM_{01} and HEM modes exactly. This model revealed several important aspects of the coupling:

1. When the coupling is due to beam asymmetry, it can be described by a single parameter that varies between 0 and 1.
2. The spatial growth rate of the "TM₀₁-like" mode *increases* slowly (10%) with this coupling parameter, whereas the corresponding value of the "HEM-like" mode drops to zero.
3. Although, the "HEM-like" spatial growth rate becomes unimportant, we have to remember that the "TM₀₁-like" mode is not a pure TM_{01} mode but rather a hybrid of TM_{01} and HEM. Consequently, due to the coupling, the HEM mode possesses the same spatial growth as the pure TM_{01} mode.
4. Based on the last conclusions and assuming that the reflection coefficients of the HEM mode from both ends are known, we determined the threshold current required for oscillation.

3D MODEL: Accumulation of electromagnetic power in the asymmetric mode causes beam to expand and eventually electrons to hit the structure wall. In order to examine this process a 3D model was developed to describe the interaction. For the typical values of the high-power, high-efficiency, traveling wave amplifiers developed at Cornell, we found that for the HEM mode to have a significant effect on the beam, the power associated with this mode at the input has to be on the order of 0.5 MW. This requires a significant asymmetry in the beam as well as a large mismatch at the tube ends in order that this power level can develop from noise. The asymmetric mode may grow from noise, may develop from slight asymmetry in the beam, from its misalignment relative to the rf structure, or from an asymmetry associated with the input or output structure.

The main conclusions of the 3D analysis are as follows:

1. The effective radius of the beam is dramatically affected by the asymmetric mode when the beam is not modulated. For example, in the case of a uniform beam, electrons hit the structure after traversing only 40% of the interaction region (12cm). In the case of a pre-bunched beam electrons almost hit the wall only after traversing ~90% of the interaction region. The length in both cases was chosen such that the TM₀₁ mode reaches saturation in the absence of the asymmetric mode.
2. In case of an initially uniform beam and for a given input power (in both modes) the normalized efficiency grows with an increasing value of the guiding magnetic field and
 - a. The efficiency of the asymmetric mode may be substantially higher than that of the symmetric mode since the HEM mode power at the input may grow due to reflections.
 - b. The coupling parameter is roughly linear with the guide magnetic field strength.
 - c. For a given guiding field the beam radius increases linearly with the initial power in the asymmetric mode.
3. In the case of a bunched beam, the efficiency of the symmetric mode may be substantially larger than that of the asymmetric mode and
 - a. The beam radius is proportional to the power in the HEM mode.
 - b. The coupling parameter scales as the square root of the HEM power.
 - c. The coupling parameter is linear with the initial phase-spread of the bunch; it decreases as this phase-spread grows.
 - d. Both the beam radius and the coupling parameter grow monotonically with the beam current.

We have employed the 1D version of the model in order to investigate the interaction process in the second stage of the experimental system - where the main interaction occurs. The results presented in the first appended article show that:

- a. misalignment of the beam does not alter dramatically the interaction of the beam with the symmetric TM₀₁ mode at the 60 MW output power level
- b. In the presence of HEM₁₁ modes we conclude that if significant asymmetry in the system occurs such that the hybrid mode may interact efficiently with the beam,

the symmetric mode may be affected even if the initial power in the asymmetric modes is small. Note that in the experiments reported above, the suppression for the reflections in the TM_{01} mode is better than 40dB and although we do not know exactly the suppression of the hybrid mode reflections, even if it is 20dB, then it is still more than sufficient to suppress the 10dB gain associated with the asymmetric modes.

- c. When the beam is on axis no significant impact on the interaction was observed even if one of the asymmetric modes has an input power of the same order of magnitude as that of the TM_{01} (200kW). A significant impact of the second hybrid mode was observed when the beam is off axis and when the power at the input was about a factor of four larger than the power in the TM_{01} mode.
- d. Finally if the initial power in the hybrid modes is large compared to that in the symmetric mode we find that the growth of the TM mode is reduced by about 4 dB and the hybrid modes reach several Mega-Watts. It should be pointed out that this behavior occurs in the case of an off axis beam. If the beam is on axis, there is no significant change in the power of the TM_{01} mode and hybrid mode affects are easily suppressed.

We conclude that the presence of the SiC absorbers as well as the tapers is crucial for the suppression of the hybrid modes as well as in eliminating the reflections in the TM_{01} mode.

Conclusions

We have carried out successful extensive investigations into the development of High Power Traveling Wave Tube Amplifiers in X-Band obtaining output power levels of ~70 MW at an efficiency of 54%. Higher powers ~120 MW were obtained when the beam voltage was increased from 700 to 800 kV.

The investigation of TWT amplifiers was extended to Ka-Band and preliminary data showed that amplifier operation was achieved and that with further development efficiencies of up to 40 % are achievable.

A new cathode ferroelectric source was developed from scratch and a 350 A, 500 kV electron gun designed and operated. Its suitability for High Power Microwave Generation was demonstrated in an X-Band single stage TWT amplifier.

Detailed theoretical work was carried out supporting the above investigations. Recently this included a detailed analysis of the role of HEM modes in TWT's.

Refereed Journal Publications

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Papers Accepted For Publication

- 1] S. Banna, J.A. Nation, L. Schächter and P. Wang
The Coupling of TM_{01} and HEM_{11} in a High-Power, High-Efficiency Traveling Wave Amplifier
Physical Review E
- [2] S. Banna, J.A. Nation, L. Schächter and P. Wang
The Interaction of Symmetric and Asymmetric Modes in a High-Power Traveling Wave Amplifier
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- [3] P. Wang, Z. Xu, J.A. Nation, S. Banna and L. Schachter
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- [1] Y. Hayashi, X. Song, J. D. Ivers, D. Flechtner, J. A. Nation and L. Schachter.
High Power Microwave Generation Using A Ferroelectric Cathode Electron Gun
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Symmetric and Asymmetric Mode Interaction in High-Power Traveling Wave Amplifiers: Experiments and Theory

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Abstract

High power microwave amplifier operation has been studied for use in a number of applications. The performance of the amplifiers has been marred, in some cases, by pulse shortening of the microwave signal. A possible source of the shortening is the loss of the beam due to hybrid HEM_{11} mode interaction with the beam. In this paper we describe experiments which investigate high power operation and the effects of HEM modes on the amplifier performance. We report the high output powers ($>50\text{MW}$) with efficient ($>54\%$) amplification of microwaves in an X-band traveling wave amplifier. In some experiments peak power levels exceeding 120 MW were measured at an efficiency of 47%. The excitation of the asymmetric hybrid electro-magnetic mode was monitored carefully, but does not seem to have a critical impact on the main interaction process in spite of the fact that its dispersion curve almost overlaps that of the symmetric interacting mode. Theoretical analysis of the interaction in a tapered traveling wave structure indicates that, even if the amount of power in the asymmetric modes at the input of the structure is comparable to that in the symmetric mode, the asymmetric modes cause no power reduction in the symmetric mode. For the case of off axis beams the TM_{01} output power may drop by about 30% and the power in the hybrid mode reach about one third of that in the symmetric mode. In order to avoid hybrid mode excitation it is necessary to suppress the reflections from both ends of the output structure several dB below the gain level of the asymmetric mode.

I. Introduction

Spectrum improvement has been one of the major concerns in the development of relativistic TWT amplifiers. Previously reported results included side-bands observed at all power levels with the output spectrum extending over $\sim 300\text{ MHz}$, which at the highest output levels carried up to $\sim 50\%$ of the power¹. The side-bands were attributed to reflections within the tube. Transit time isolation of the input and output of the amplifier was subsequently successfully used to prevent the reflections caused by the output section from reaching the input end during the beam pulse duration and hence eliminated the side bands. The transit time isolation method is based on the use of a low group-velocity in the amplifier to achieve the isolation of the input and the output. The technique was of limited use due to limitations arising from low structure group velocity. For example, the high energy density obtained for a given power translates into large electric fields ($100\text{-}200\text{ MV/m}$ for $\sim 100\text{ MW}$ power). This limits the maximum extractable power. The transit time isolation also would make this method very difficult to use in long pulse devices.

In the experiments described in this paper we make extensive use of slow wave structure tapers to minimize reflections, and use SiC severs and absorbers to further reduce reflected signals. We demonstrate that the use of appropriately distributed severs and absorbers eliminates the sideband formation without limiting the high beam power to microwave conversion efficiencies. Particle-in-cell (PIC) simulation² using the Magic Code³ has shown that a combination of tapering of the iris aperture with each successive period until the desired aperture is reached together with extensive use of absorbers can lower the reflection level dramatically and is useful in TWT amplifiers with ≤ 40 -50 dB gain over the instantaneous bandwidth of the amplifier.

We further report in this paper a series of experiments designed to examine the importance of hybrid modes in high output microwave power (~ 100 MW) X-band traveling wave tube amplifiers. Two amplifiers were designed and tested such that in one case the passbands of the lowest order TM and HEM modes almost overlapped, while in the other the modes were well separated. Hybrid modes have been shown to be important in particle accelerators and may be responsible for the microwave pulse shortening observed in high power microwave sources⁴. In these experiments the hybrid modes were found to be unimportant and the microwave pulse duration was equal to that of the primary pulse power even at output power levels of 120 MW.

High beam to microwave conversion efficiency is another driving issue in TWT investigations. In the transit-time isolation experiment reported above the efficiency was $\sim 20\%$ ⁵. Two of the possible reasons for low conversion efficiency are the re-absorption of microwave energy by the 'used' electrons and inefficient beam bunching. Coaxial extraction⁶ and traveling wave compression⁷ concepts have been proposed to solve these two problems. The use of a high phase velocity input section followed by a low velocity output section has been reported elsewhere and was referred to as using as step taper. It is useful in enhancing the system microwave conversion efficiency. In the coaxial extractor we use a coaxial beam dump to decouple the microwaves from the electrons and to simultaneously convert the TM_{01} mode into a TEM mode. The elimination of the microwave re-absorption by the beam electrons increases the amplifier efficiency and has been demonstrated using PIC simulations and in experiments at low efficiency ($\sim 20\%$)⁸. The efficacy of the coaxial extraction method needs to be further verified, however, in high efficiency, high power operation. The second efficiency enhancement technique relies on the use of a traveling wave structure with a cold phase velocity considerably above the value required by the synchronous operation condition to produce efficient beam bunching. This concept, which has been developed using PIC simulations⁷, showed that a high phase velocity bunching section followed by a lower phase velocity output section can then be used to efficiently extract the energy from a tightly bunched electron beam. However, the off synchronous 'tuning' decreases the growth rate within the structure, increases its length, and enhances the possible growth of hybrid modes. These modes can efficiently drive the electrons to the tube wall and cause beam break-up instability (BBU) problems⁹. These effects will nullify the improved TWT amplification process and cause microwave pulse shortening.

In the last section of this study we present simulation results based on a model reported elsewhere¹⁰.
¹² These reveal that as long the beam is aligned with the structure to better than the beam radius excitation of the hybrid modes is small, even if we assume that the power at the input is four times that in the symmetric mode.

In the following sections we describe the experimental arrangements used and then describe the results showing high efficiency amplification in the TM_{01} mode without serious competition from the hybrid modes. This coupling is further investigated theoretically.

II. Experimental Arrangement

We show schematically the experimental arrangement for the amplifiers in Figure 1. An 80 nsec duration pulsed electron beam having an energy of 700kV and a current of ~ 200 A in a 7 mm diameter beam is guided by a 1m long, 0.5T, axial magnetic field through the structures. The beam voltage and current are flat to better than $\pm 4\%$ and 2% respectively. The input microwave signal to the amplifier is provided by a magnetron coupled to the amplifier through a sidearm and ranges from a few hundred watts up to about 30 kW. The base pressure in the system is $\sim 10^{-6}$ Torr. Details of the differences between the amplifiers (referred to as Amplifiers A and B respectively) are indicated in Table 1.

In both cases the amplifier uses a dielectric preamplifier stage. The dielectric used, Boron Nitride ($\epsilon_r = 4.7$), has a length of 12 cm (including two 0.5cm long tapers) and internal and external radii of 12.2 and 15.7 mm respectively. The input and output ends of the dielectric are tapered to minimize reflections. The stage is designed such that the cold wave phase-velocity $\beta_{ph} = 0.91$ at 9.0 GHz, is synchronous with the electrons. At 9.48 GHz, the highest frequency used in these experiments, the normalized wave phase velocity has dropped to $\beta_{ph} = 0.87$. The spatial growth rate for synchronous electron flow is calculated to be 1.74 dB/cm and the gain as 9.6 dB. The second stage of the amplifiers uses a non-uniform disk-loaded structure. The disk loaded structures have two regions, the first a 'long' bunching section, and the second an output section. The two sections are joined by a short disk loaded taper. The relevant design figures for amplifiers are summarized in Table 1 and by the dispersion relations shown in Figure 2. The dispersion curves include the axi-symmetric TM_{01} mode and the lowest branch of the dipole like HEM_{11} mode. The input and output to the second stage consists of a tapered disk loaded guide designed to keep reflections to a minimum. In both amplifiers the periodic length of the disk-loaded sections is 7.5 mm, of which 1.5 mm comprises the disk. The periodicity corresponds to phase advance per cell of $\sim \pi/2$ at 9 GHz.

The dielectric and disk loaded sections are separated by a sever consisting of 4 orthogonal SiC fins joined to the outside wall of the tube and tapering in from ~ 17.13 mm to 11.1 mm radius. Each fin has a length of 11.5 cm and a thickness of 3 mm. The single pass attenuation of the sever is greater than 17.5 dB in the TM mode, and the power reflection coefficient of the sever less than 1%. Similarly designed absorbers are located at the input of the amplifier and after the output taper. In the former case a 6 finned structure is used, whereas after the output taper a 4 fin absorber was used. The sever and absorbers are essential for good operation of the amplifier, since it is important to limit feedback from the amplifier output to the input for both symmetric and asymmetric modes.

The microwave signal from the magnetron is coupled into the cylindrical waveguide immediately following the front-end absorber. Some tuning is available from a second rectangular guide arm located directly opposite to the input arm. The tuner is used to minimize coupling into the TE_{11}/TM_{11} modes of the circular waveguide. The input coupler tuning does not couple the maximum power into the circular guide but does ensure that more than 90% of the input signal is in the required TM_{01} mode. The sever following the dielectric amplifier section also serves to further reduce the amplitude of the dipole mode injected into the disk loaded amplifier. The symmetric mode is also reduced, but

the beam bunching is retained through the sever section, and serves to allow wave reconstruction at the entrance to the disk loaded amplifier sections.

In some of the experiments to be described in the following sections a coaxial output configuration, consisting of a coaxial hollow metallic tube with 10.6 mm outer diameter, was used to de-couple the electron beam from the amplified microwave signal. The coaxial transition also functions as an efficient mode converter from the symmetric TM mode in the circular tube to a TEM mode in the coaxial section. The inner of the coaxial conductor also serves as a beam dump for the electrons. The transition is typically designed to operate correctly close to the end of the output section and before the wave has speeded up in the tapers. We show in Figure 3 the power reflection coefficient for structure A with and without the coaxial mode converter/beam dump, including the 4 cell transition section between the buncher and output sections of the amplifier. For the complete frequency range used the power reflection coefficient is less than 3%. We also show in the same figure the reflection coefficient for structure B without the mode converter. In this case the reflection is less than 2% for frequencies in the range 9.0 to 9.2 GHz and rises rapidly thereafter. In the experiments reported here the coaxial converter was only used with amplifier A.

Measurements of the microwave amplitude are made immediately following the dielectric amplifier and after the disk loaded amplifier output taper. Measurements are made within the coaxial guide, when the inner conductor is in place. The microwave signal is measured using previously calibrated electric field (E field) probes located in the walls of the guide. The detected signal is split into two parts with one going to a crystal detector to determine the power envelope and the other going to a double balanced mixer where the frequency of the amplified wave is checked. The IF signal is also checked to determine the spectral content of the amplified pulse.

III Experimental results

In this section of the paper we describe the experimental results obtained for the two amplifiers studied. In both configurations the same dielectric-loaded waveguide was used as the input buffer amplifier. The role of the first stage is to absorb the injected microwave signal and to pre-modulate the beam. We require a low gain for this stage because the reflection from the input coupler junction is relatively large and it is easy, if the gain is too large, to develop side bands from the reflections. Following the dielectric section we have a (four vane) sever. A four vane SiC absorber is also located at the output end of the disk-loaded amplifier. Both the sever and the absorber have low reflection coefficients and may be used in amplifiers having gains of order 40-50 dB. Note that the sever effectively eliminates the amplified signal from the first stage but allows propagation and further bunching of the electron beam prior to the tapered entrance to the disk loaded sections.

High Power and High Efficiency Operation:

In Figures 4 shows a typical output and beam data taken from amplifier B (at 9.145GHz) at a location following the output taper; no mode-converter was used. Similar output was measured for amplifier A and the results were published in Ref.13. The picture shows the beam voltage and current waveforms, together with the detected microwave power envelope. Part of the detected signal is fed to a double balanced mixer, which uses the signal from an X-13 klystron as the local oscillator. The IF signal is displayed in both cases together with an FFT of this signal. Note that the microwave power signal follows the power envelope of the beam and that there is no evidence of

pulse shortening. For amplifier B the data shown corresponds to an output power 45 MW; the input power to the amplifier was 1.2 kW. Similar data¹³ was measured at the maximum output power of 78 MW using amplifier A and *with* the output mode-converter in place. The conversion efficiency during the 'flat top' of the pulse was 54 %. Allowing for the actual rise and fall time of the beam pulse, and for which amplification did not occur, this data yielded a 43 % energy conversion efficiency. With a longer pulse duration and/or better rise time the power and energy conversion efficiencies should become closer to the measured power conversion efficiency. In the absence of the output coupler the best performance of the amplifiers showed output powers of 63 MW (for A) and 58 MW (for B) from the 700 keV beam. We summarize the top performance of the two amplifiers in Table 2.

Experiments have also been carried out with a 300A beam current and at a beam energy of 800 keV using amplifier A. Output signals similar to those shown in Figure 4 have been obtained but at power levels of up to 120 MW corresponding to an efficiency of 47%. These results were obtained in the absence of the coaxial beam dump. Higher power levels and efficiencies would be expected with the output converter in place.

Amplifier Gain and Frequency Response: Figure 5 shows a plot of the output power versus the input power for amplifier A at 9.48GHz *without* the coaxial mode converter. There is a well-defined linear operational range. The measured gain at 9.478 GHz, obtained with input signal levels of less than 10 kW, is about 35 dB. The signal saturates at approximately 60 MW. Less detailed data was obtained for structure B where the gain was approximately 43 dB at 9.145 GHz. In Figure 6 we show plots of the frequency response of the amplifiers indicating that the 3 dB bandwidth is at least 300 MHz with that for amplifier A being, as expected, greater than that for amplifier B. It is noted that above 9.3 GHz the fluctuation level in the output of amplifier B increased significantly. This is expected considering the increase in the reflection coefficient of the output section above 9.2 GHz. In all other cases however the amplifier outputs are smooth and the measured FFT signals are similar to those illustrated in Figure 4.

Hybrid Mode Excitation: As indicated above there was no evidence of shortening of the microwave pulse in the experiments. Note that in amplifier A the hybrid mode dispersion relation is almost superimposed on the TM mode, whereas in amplifier B the modes are well separated – see Figure 2. We have in addition carried out a detailed check of the output at frequencies other than the input magnetron frequency. In these experiments, using amplifier A, we used a high pass filter to eliminate the amplified signal at the input wave frequency and searched using the power envelope detector and a double-balanced mixer for signals at other frequencies, especially at the expected hybrid mode interaction frequency. Some microwave power was detected between 9.4 and 9.8GHz with a peak power level about 25-30 dB lower than that of the amplified signal. As may be checked in Figure 2(a), amplification in the TM_{01} mode at the frequency, 9.6 GHz corresponds to synchronous operation with the electrons. Synchronous interactions in the HEM_{11} mode would occur around 10.5 GHz. No signal has been detected at this frequency at power levels down to ~40 dB lower than that of the amplified TM_{01} signal. Similar results were obtained using the second amplifier.

We have attempted to deliberately enhance the probability of hybrid mode excitation by use of an asymmetric beam. In this case the beam cross section was made approximately elliptical with a two to one variation in the major and minor radii. The asymmetric beam was propagated through the tube in two orthogonal orientations. In neither case did we detect any hybrid mode coupling. This result

was reinforced by checking the detected signal in two orthogonal planes. The experimental results show an azimuthal symmetric field distribution, another indicator of the absence of HEM_{11} mode. The asymmetric HEM_{11} mode signal level was insignificant even when the input wave excitation was preferentially made using a TE_{11} or TM_{11} mode. Finally we propagated a regular pencil beam off axis so that one part of its outer extremity propagated along the guide axis. Once again there was no evidence of significant growth of the hybrid mode. Further reinforcement of these results was obtained from simulations that rely on a theoretical model¹⁰⁻¹². These results will be presented following a discussion of the experimental results.

IV Discussion

The data presented above showed the efficient operation of two different X-band TWT's using non-uniform slow wave structures, in which traveling wave bunching sections have cold phase velocities well above that determined by the synchronous condition. The amplifier performance came relatively close to the PIC code predictions -58%. The achieved power and efficiency level was comparable to that obtained in recent high power klystron experiments^{14,15}. The beam bunching in the amplifiers develops in the traveling wave bunching sections and the power extraction occurs mainly in the short traveling wave output sections. For a given beam the interaction is determined by the phase velocity in the slow wave structures. The two amplifiers have different cell dimensions, and therefore different interaction impedances, passbands and lengths. However the cold wave phase velocities and phase-advance per cell at 9.0 GHz for TM_{01} mode were kept constant at $\pi/2$ for both amplifiers. As a result the experimental performance of the amplifiers is similar.

Operation of the buncher in a regime where the cold phase-velocity is high, entails lower gain and consequently requires a longer interaction distance to achieve a given degree of beam bunching. In long uniform structures, the probability of excitation of the BBU instability, associated with the growth of non-azimuthal symmetric HEM_{11} modes, is increased. Its effect would be to drive the beam to the wall¹⁹. The two structures examined have different gain characteristics and dispersion relations. Specifically their gains differ by about 10 dB and the HEM_{11} mode overlaps the TM_{01} mode for structure A and is separate from it in structure B. Structure A is also much longer than structure B. We have not found any experimental evidence of excitation of HEM modes in either structure, as indicated by the absence of wave excitation at the expected HEM mode interaction frequencies, and by the propagation of the injected beam current throughout the whole structure without significant loss.

The measured frequency-spectrum of the amplifiers approximates that of a square pulse modulated with a single frequency signal, and its ~20-30 MHz width is approximately equal to that expected for the pulse power duration. The measured single frequency spectrum is indicative of the absence of reflections and the excitation of spurious modes. The three severs and the transition sections contributed to the effective suppression of reflections inside the structures. It is observed in the experiment that the first absorber is essential for stable performance of the dielectric modulation stage and the overall amplifier performance. Structure B has higher gain and higher reflections above 9.2 GHz. As a result the relevant spectral width is somewhat broader. Further minimization of reflections could be achieved by exponential tapering of the cells' inner radii within the transition sections. In the experiments linear tapering was adopted for experimental convenience. It is noteworthy that these spectrum improvement methods do not impose any pulse duration limitations or sacrifice any of the power handling ability of the structures. The successful operation of the

amplifiers over the available magnetron frequency range demonstrates that these methods also enable broad-band operations.

Theoretical models developed in the past for the description of the interaction in a traveling wave structures, focused exclusively on the symmetric mode. Recently, in parallel with the experimental studies reported here, we developed¹⁰⁻¹² a theoretical model that takes into consideration asymmetric modes. In principle, it calculates the full 3D dynamics of the particles and 3D variations of the electromagnetic field though we assume that the interaction affects the field variation only in one direction – parallel to the main motion of the electrons. We shall employ a simplified version of the model in order to investigate the interaction process in the second stage of the system where the main interaction occurs. The results presented focus on Structure A ignoring the tapers at the input and output end. It includes the 45 cells of the buncher section, the 7 cells of the output region, and 4 transition cells. The operation frequency of the TM₀₁ mode is assumed to be 9.2GHz. Other than the symmetric mode it is assumed that there might be two additional asymmetric modes in the system: one (HEM₁₁) can be excited by the beam in the buncher which will oscillate at 10.866GHz and a second which may be excited by the beam in the output section which will oscillate at 10.227GHz. Table 3 summarizes the characteristics of the modes in the two main regions. The italics represent the corresponding figures for the mode operating in the “complementary” region, for example, if the beam excites the first HEM₁₁ mode (10.227GHz) in the output its phase velocity is 0.907c, but in the buncher section its phase velocity is 1.035c. In a similar way, the beam generates in the buncher the second HEM₁₁ mode at 10.866GHz and when this wave propagates in the output section its phase velocity is 0.634c.

Figure 7 illustrates the variation of the phase velocity of the HEM modes along the interaction region assuming a smooth linear transition between the bunching and output regions. The lower frame illustrates the (normalized) interaction parameter α for the corresponding modes

$$\alpha = \frac{eI}{m c^2} \frac{Z_{int}}{\pi R_{int}^2} \frac{D^2}{2P} ; Z_{int} = \frac{1}{2P} \pi R_{int}^2 E_z^2$$

here D is the total length of the structure (56periods), P is the average power in the specific mode and E_z is the amplitude of the longitudinal electric field on axis. With these quantities in mind we employ a 1D version of the model mentioned above that is represented by the following set of equations

$$\begin{aligned} \frac{d}{d\xi} \left(\frac{a_1}{\sqrt{\alpha_1}} \right) &= \sqrt{\alpha_1} \langle e^{-j\chi_{i,1}} I_0(\bar{\Gamma}_1 \bar{\Gamma}_1) \rangle, \quad \frac{d}{d\xi} \left(\frac{a_2}{\sqrt{\alpha_2}} \right) = \sqrt{\alpha_2} \langle e^{j\phi_1 - j\chi_{i,2}} I_1(\bar{\Gamma}_2 \bar{\Gamma}_1) \rangle, \quad \frac{d}{d\xi} \left(\frac{a_3}{\sqrt{\alpha_3}} \right) = \sqrt{\alpha_3} \langle e^{j\phi_1 - j\chi_{i,3}} I_1(\bar{\Gamma}_3 \bar{\Gamma}_1) \rangle, \\ \frac{d}{d\xi} \chi_{i,1} &= \frac{\Omega_1}{\beta_i} - K_1, \quad \frac{d}{d\xi} \chi_{i,2} = \frac{\Omega_2}{\beta_i} - K_2, \quad \frac{d}{d\xi} \chi_{i,3} = \frac{\Omega_3}{\beta_i} - K_3 \\ \frac{d}{d\xi} \gamma_i &= -\frac{1}{2} \left[a_1 e^{j\chi_{i,1}} I_0(\bar{\Gamma}_1 \bar{\Gamma}_1) + a_2 e^{j\chi_{i,2} - j\phi_1} I_1(\bar{\Gamma}_2 \bar{\Gamma}_1) + a_3 e^{j\chi_{i,3} - j\phi_1} I_1(\bar{\Gamma}_3 \bar{\Gamma}_1) - j a_{sc} e^{j\chi_{i,1}} \langle e^{-j\chi_{i,1}} \rangle + c.c. \right] \end{aligned}$$

the indices represent 1 - TM_{01} mode, 2 - $HEM_{11}(10.277\text{GHz})$ and 3 - $HEM_{11}(10.866\text{GHz})$. In addition the space charge term associated with the TM_{01} mode is given by $a_{sc} = eI\eta/\pi mc^2 (\omega D/c)^{-1} (D/R_b)^2$ and we neglect the other space-charge terms corresponding to the other two modes; πR_b^2 is the electron beam area.

The first question considered was whether misalignment of the beam may directly affect the interaction with the TM_{01} mode. Figure 8 illustrates the buildup of the power (and efficiency) along the second stage of the amplifier for two cases. The solid line represents the case when the beam is on the symmetry axis of the structure, and the dashed line when the beam is off axis and its edge grazes the symmetry axis of the structure. In both cases the other two HEM_{11} modes are assumed to be zero along the entire interaction region. We observe that the two cases are virtually indistinguishable and power levels of 60MW at 40% are achievable (for a 720kV, 200A beam). We conclude that for this typical set of parameters, misalignment on its own does not alter dramatically the interaction of the beam with the symmetric TM_{01} mode. In this simulation and in the others that follow, it is assumed that the space-charge wave modulation at the input of the structure (buncher) corresponds to an axial electric field of 0.73MV/m, which in turn corresponds to a 200kW input power.

At this point we "turn on" the HEM_{11} modes and it is assumed, as a result of reflections, that there is some amount of power in addition to that in the TM_{01} mode – specifically we assume $P_1 = P[HEM_{11}, 10.227\text{GHz}] = 34\text{kW}$ and $P_2 = P[HEM_{11}, 10.866\text{GHz}] = 75\text{kW}$. Both are significantly smaller than $P_{TM_{01}}$ at the input to the disk-loaded structure. Figure 9 shows results of the simulation which includes all three modes with the beam on and off the waveguide axis. The top frame illustrates the results when the beam is on axis and shows that the power remains unaffected by the presence of the asymmetric modes. It reaches the 60MW level and the amplification of the asymmetric modes is insignificant and is such that the severs, included in the experimental system, should readily suppress them. When the beam is off axis the simulation shows a 10MW drop in the power of the TM_{01} mode – the dashed line shows the unaffected mode for comparison. In addition we observe an increase in the output power of the asymmetric modes to order of 1 MW corresponding to at least 10dB amplification compared to the on axis case (top frame). It is interesting to note that although P_1 is supposedly excited in the output section it interacts efficiently with the beam in the buncher region – this is because its phase velocity is larger than c and its interaction impedance is ten times larger there than in the output region. In fact, in the output section, it seems that the wave loses energy. P_2 at the same time increases monotonically and it interacts efficiently in both the buncher and output sections, in spite the fact that the mode was "supposed" to interact primarily in the buncher region. The conclusion from this series of simulations is that when significant asymmetry in the system occurs such that the hybrid mode may interact efficiently with the beam, the symmetric mode may be affected even if the initial power in the asymmetric modes is small. Note that in the experiments reported above, the suppression for the reflections in the TM_{01} mode are better than 40dB and although we do not know exactly the suppression of the hybrid mode reflections, even if it is 20dB, then it is still more than sufficient to suppress the 10dB gain associated with the asymmetric modes.

Let us now assume that due to impedance mismatch at the end of the structure, the amount of power that develops in one of the asymmetric modes is of the same order of magnitude as that for the TM_{01}

beam modulation (200kW). When the beam is on axis no significant impact on the interaction was observed. However, when the beam is off axis we observed a significant reduction of the TM mode output power as shown by the upper frame in Figure 10 which illustrates the spatial development of the power for the three modes for $P_1 = 0.21$ MW and $P_2 = 0$ W. The power in the symmetric mode dropped below 40MW and the power of the first hybrid mode increased by more than 10dB to about 3MW; the second hybrid mode in these conditions was unimportant. A significant impact of the second hybrid mode was observed when the beam is off axis and when the power at the input was about a factor of four larger than the power in the TM_{01} mode i.e. $P_2 = 0.83$ MW. The power in this case increases by almost 15dB. The reduction in the power in the TM_{01} mode is similar to that in the previous case.

The last result from this set of simulations is shown in Figure 11. It illustrates the dynamics of all three modes when the *initial* power in the hybrid modes is large (>0.8 MW) comparing to that in the symmetric mode (0.2MW). The latter grows by less than 25dB to about 23 MW and the hybrid modes grow to 4 and 6 MW. It should be pointed out that this behavior corresponds to the case of a beam off axis. If the latter is on axis, there is no significant change in the power of the TM_{01} mode which reached the 58 MW level. Even in these conditions namely, power levels in the hybrid modes at the input reaching the 1MW level, the hybrid modes are relatively easily suppressed assuming that the overall reflection coefficient from both ends is at least 20dB.

All the frames in Figures 9-11 show that the phase mismatch plays an important role in the interaction of the asymmetric modes since the power fluctuations in space of these modes is by far more significant than the symmetric mode – that grows monotonically until it reaches saturation. It should be emphasized that no reflected waves are explicitly taken into consideration in this formulation therefore the power fluctuations are not due to interference.

These simulations provide a quantitative trend regarding the development of hybrid modes in slow wave structures. It is quite evident that if the electron beam is well aligned, then the excitation of hybrid modes is very unlikely if the overall reflection coefficient is several dB larger than the gain. Therefore the presence of the SiC absorbers as well as the tapers is crucial for the suppression of the hybrid modes as well as eliminating the reflections in the TM_{01} mode. One important conclusion of the present analysis is that hybrid modes may interact fairly efficiently with an electron beam even in a region where they are not “supposed” to, since their phase velocity is larger than c – as is the case with the first hybrid mode that interacts very efficiently with the beam in the buncher region. In this regard, the tapering in our structure does not seem to cause a de-coherence of the hybrid modes however, this may be also attributed to our tacit assumption that the transition from one section to another is adiabatic and no wave is reflected. Finally, as regards these calculations, the magnetic field was tacitly assumed here to be very large and no transverse motion was considered, i.e. the calculation considers the HEM wave growth but not its effect on the transverse dynamics. The latter generates a positive feedback, that with a finite magnetic field, is responsible to beam break-up. As the beam expands due to significant radial force, the coupling of the beam to the wave(s) is larger, therefore the radial force increases and the beam further expands. In earlier publications [12-13] we have shown that the magnetic field is crucial in determining the beam expansion in either the case of an high efficiency TM_{01} interaction, or in the presence of hybrid modes, or both. The experimental data presented in this study indicates that a typical magnetic field of 0.5T is sufficient to confine a 200-300A beam even when the efficiency is as high as 54%.

VI Conclusions

In conclusion, we have demonstrated experimentally that non-uniform disk-loaded traveling wave amplifiers may be used to produce high efficiency, high power microwave signals. The use of adiabatic transitions between sections together with the extensive use of severs suppresses hybrid modes and eliminates sideband development. Microwaves powers of up to 120 MW have been generated. The maximum power conversion efficiency was ~47 % with no center conductor, and 54% when a center conductor was used. The energy conversion efficiency reached a maximum value of 43 %. Spectra with 20-30 MHz bandwidth have been obtained. The amplifiers have an instantaneous bandwidth of at least ± 2.5 %. Pulse shortening and hybrid HEM_{11} modes were not observed in the amplifiers, even when strong asymmetries were introduced in the beam cross-section and/or the input wave .

The theoretical investigation focused on the interaction of the beam with the hybrid modes that may develop in the structure. It was shown that the typical gain in a 56 periods long structure of either one of the hybrid modes is less than 15dB. Since no oscillation was observed at the frequencies of the hybrid modes we conclude that the overall reflection coefficient is at least -15dB and probably smaller. Other than strong suppression with absorbers and tapers, our study indicates that beam alignment is important and the combination of misalignment and reflections may effect the operation of the system. Finally, we show that the hybrid modes may interact efficiently with the beam, in the presence of a symmetric mode, even if its phase velocity is more than 30% higher than the speed of light. Therefore a mode that may be excited by the beam in a specific region may interact with the beam over a substantially extended region – provided that the TM_{01} mode is also present. The limited impact of the hybrid mode on the interaction of a beam with a symmetric mode and beam in a traveling wave structure has important implications on the feasibility of generating high power microwave in the millimeter regime using traveling wave structures.

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<u>Section</u>		<u>Structure A.</u>	<u>Structure B.</u>
Input Taper		17.13—11.75 mm in 10 cells	14.8 – 8.0 mm in 14 cells
Buncher	R_{ext}	17.13 mm	14.8 mm
	R_{int}	11.75 mm	8.0 mm
	# Cells	45	24
	β_{ph} at 9.0 GHz	1.05	1.05
	β_{ph} at 9.48 GHz	0.94	0.78
	Spatial Growth Rate	1.43 dB/cm at 9.0 GHz	3.3 dB/cm at 9.0 GHz
	Interaction Impedance	49 Ohms	608 Ohms
Transition Taper	R_{ext}	17.13 mm	14.8-15.2 mm in 4 cells
	R_{int}	11.75 – 10.75 mm in 4 cells	8.0mm
Output Section	R_{ext}	17.13 mm	15.2 mm
	R_{int}	10.75 mm	8mm
	# Cells	7	7
	β_{ph} at 9.0 GHz	0.84	0.84
	β_{ph} at 9.48 GHz	0.72	0.6
	Spatial Growth Rate	1.41 dB/cm at 9.0 GHz	2.79 dB/cm at 9.0 GHz
	Interaction Impedance	29 Ohms	224 Ohms
Output Taper		10.75--17.13 mm in 14 cells	8 –15.2 mm in 14 cells

Table 1. Structure Parameters

	Amplifier A with mode converter	Amplifier A without mode converter	Amplifier A without mode converter (high current)	Amplifier B without mode converter
Output Power (MW)	78	63	120	58
Input Power (kW)	31	23	25	5.1
Frequency (GHz)	9.21	9.478	9.21	9.145
Power Conversion Efficiency (%)	54	46.8	47	46.5

Table 2. Typical Amplifier Operation Parameters

	Buncher	Output
TM ₀₁	$f=9.2\text{GHz}$	$f=9.2\text{GHz}$
	$\beta_{ph}=0.9976$	$\beta_{ph}=0.7965$
	$Z_{int}=0.6\text{k}\Omega$	$Z_{int}=0.4\text{k}\Omega$
	$R_{int}=11.75\text{mm}$	$R_{int}=10.75\text{mm}$
HEM ₁₁	$f=10.227\text{GHz}$	$f=10.227\text{GHz}$
	$\beta_{ph}=1.035$	$\beta_{ph}=0.907$
	$Z_{int}=37.66\text{ k}\Omega$	$Z_{int}=3.34\text{ k}\Omega$
	$R_{int}=11.75\text{mm}$	$R_{int}=10.75\text{mm}$
HEM ₁₁	$f=10.866\text{GHz}$	$f=10.866\text{GHz}$
	$\beta_{ph}=0.907$	$\beta_{ph}=0.634$
	$Z_{int}=1.54\text{ k}\Omega$	$Z_{int}=0.37\text{ k}\Omega$
	$R_{int}=11.75\text{mm}$	$R_{int}=10.75\text{mm}$

Table 3.: Operation parameters for Structure A as used in the simulation

Figure Captions

Fig. 1: Schematic of the experimental arrangement for amplifier A

Fig 2: Dispersion relations of structure A and structure B for the TM_{01} and HEM_{11} lower modes. The relations are shown for both the buncher and output sections of both amplifiers.

Fig.3: Power reflection coefficients from the output end of the disk loaded amplifiers. The two curves shown for amplifier A correspond to the situation with and without the coaxial output section, whereas the reflection coefficient is only indicated for amplifier B in the case without the coaxial output section.

Fig 4: (a) Typical time dependence of the beam voltage (upper trace), beam current (middle trace) and the amplified microwave signal (lower trace) for amplifier B at 9.145 GHz. (b) Heterodyne signal for amplifier B data given above and, (c) FFT of the heterodyne signal in (b).

Fig.5: Variation of the output power while varying the input microwave power level for amplifier A at 9.478GHz. The center conductor was not present when this data was obtained.

Fig.6: Frequency response for both of the amplifiers.

Fig.7: Variation in space of the phase velocity and of the coupling coefficient for the three relevant modes.

Fig.8: The buildup of the power (and efficiency) along the second stage of the amplifier for two cases. The solid line represents the case when the beam is on the symmetry axis of the structure, and the dashed line when the beam is off axis and its edge grazes the symmetry axis of the structure. In both cases the other two HEM_{11} modes are assumed to be zero along the entire interaction region.

Fig. 9: Results of the simulation which includes all three modes with the beam on and off the waveguide's axis. The top frame illustrates the results when the beam is on axis and on the bottom frame when the beam is off axis – the dashed line shows the unaffected mode for comparison. The initial power in the hybrid modes is significantly smaller than in the symmetric mode.

Fig.10: *Top frame.* Interaction when the power of the first asymmetric mode is of the same order of magnitude as that for the TM_{01} beam modulation (200kW). *Bottom frame.* The amount of power in the second asymmetric mode has to be four times larger for a similar performance.

Fig. 11: The dynamics of all three modes when the *initial* power in the hybrid modes is large ($>0.8MW$) comparing to that in the symmetric mode (0.2MW).

Figure 1 [Wang et al.]

Figure 2 [Xiang et al.]

Figure 2. Filtered data

Figure 4 [Wang et. al.]

Figure 5 [Wang et al.]

Fig 6 [Liang et al.]

Fig. 7 [Wang et al.]

Fig. 8 [Wang, et al.]

Fig. 9 [Wang, et.al.]

Fig. 10. [Kilung et al.]

Fig. 11 [Wang et al.]

High Power Microwave Generation Using A Ferroelectric Cathode Electron Gun

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Abstract. A two-stage 500 kV, 200A, ferroelectric electron gun has been designed, fabricated, tested and used in an High Power Microwave Amplifier Experiment. We report on the operational characteristics of the gun including measurements of the beam dynamics. The optimum conditions for application of the trigger and its timing are also reported. Faraday cup measurement shows that the beam radius is 4.5 mm in good agreement with simulation. The gun is designed for use in traveling wave tube amplifiers (TWT) and testing of an X-band amplifier driven by the gun is reported. A peak output power of 5.9 MW has been observed from a single stage amplifier driven by a 100 A, 450 kV beam. This corresponds to energy converging efficiency of 13.1% and is the first observation of high power (~MW) microwave generation using the beam generated from a ferroelectric cathode

INTRODUCTION

Ferroelectric cathodes have been developed in our laboratory over the last several years as a possible alternative to a thermionic cathode. Among the possible advantages of a ferroelectric cathode are room temperature operation, control of the emission by an external trigger pulse and most importantly high electron current density.

During the last decade the electron emission from a ferroelectric cathode has been investigated in several laboratories^{1,2,3}. As part of this effort we have studied the use of ferroelectric cathodes for use in electron guns, with the development of a suitable source for high power microwave generation our principle application^{4,5,6}. In this paper we describe our gun design and report on its performance in an X-band TWT amplifier. We have developed a suitable electron gun using a 2-stage compression scheme in which the beam is initially electrostatically compressed and subsequently magnetically compressed to its final radius of 4.5 mm. This arrangement allows us to obtain a sufficiently large beam current in matched beam with the desired radius.

A single stage X-band traveling wave tube amplifier has been designed and constructed for use with the gun. In these experiments microwave amplification of order 30 dB has been achieved and output powers of several MW have been observed. This is the first observation of microwave generation on the order of MW from a beam generated from a ferroelectric cathode.

In the following sections we present results extending our previously reported study of ferroelectric emission in a diode to electron beam generation at beam energies of up to 550 keV⁵ and demonstrate its use in an HPM amplifier experiment. The beam quality has been determined by measurements of the beam emittance and confirmed by the observation of microwave amplification in X-band.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown schematically in Fig. 1. The cathode gun assembly is connected to the modulator described previously^{5,6}. The gun geometry, which was designed using data from the aforementioned diode experiments, uses a planar cathode in a modified Pierce geometry. The emitting area can be made relatively small to produce the required beam current as a result of the high current density available from the ferroelectric cathode. In order to obtain a high electron current density the electric field on the ferroelectric cathode must be sufficiently high. On the other hand, in order to obtain the required electrostatic focussing, the emitting surface has to be recessed from the cathode-mounting surface. This causes the electric field on the cathode surface to be significantly reduced compared with that of our earlier work⁵. These constraints have lead us to select an operating current density at the cathode of $\geq 20 \text{ A/cm}^2$. The emission density is competitive with that available using thermionic cathodes.

Coupling these conflicting requirements has led us to a two-stage gun design, in order to satisfy both the requirements simultaneously. The first stage of the electron gun resembles a Pierce gun with the cathode located in the fringing magnetic field of the small diameter solenoid. In this region the beam is mainly compressed by the applied electric field. The geometry is chosen so that the beam compression follows the magnetic flux lines. The first stage of the gun provides a matched beam with relatively high current. However, the beam radius is still rather large and further compression is achieved in the second stage by adiabatically increasing the magnetic field within the drift tube.

An overview of the final geometry adopted is illustrated in Fig.1, in which the dimensions are all

Figure 1: Experimental arrangement for the microwave amplification using an electron gun with a ferroelectric cathode.

shown in millimeters.

Shown in Fig. 2 is an EGUN simulation result for the gun dynamics. In this figure $z=0$ is defined as the axial position of the anode plate. The magnetic fields at the flat portion of first and second

Figure 2. EGUN Simulation of Electron Gun Design

stages are 3.15 kG and 6.84 kG, respectively. The plot shows that the beam has been compressed from its initial radius of 15 mm down to 6.6 mm by the first stage compression. The second stage of the magnetic field coil, which starts at $z = 120$ mm, and is characterized by a slowly increasing magnetic field from 3.15 kG to 6.84 kG between 70 mm and 210 mm. In this region, the beam radius has been compressed from 6.6 mm down to 4.5 mm. Similar results for the beam dynamics have been found using the PIC code MAGIC. The closely identical results between these extreme cases (thermionic emission in EGUN and field emission in MAGIC) gives confidence that the ferroelectric emission will lie close to these results.

The ferroelectric cathode used in this experiment is a planar LZT-2 sample. The dimensions of the ferroelectric cathode are given in Table 1. The vacuum electric field at the emitting surface is 72 kV/cm. To avoid breakdown and emission from parts other than the emitting area, both the cathode and anode surfaces are relatively flat in comparison with the usual Pierce geometry. The maximum electric field on the cathode mount designed is 210 kV/cm, and is close to limit at which the stainless steel support will start to emit.

Table 1. Ferroelectric Cathode Parameters

Diameter	38.1 mm (1.5 in)
Thickness	1 mm
Thickness of silver layer	10 μ m
Width of the silver strip	0.4 mm
Emitting area	708 mm ²

The ferroelectric cathode is coated with a 0.2 mm silver grid on its front surface and a uniform silver layer on its back. The trigger pulse is adjusted to start slightly before the maximum of the gun voltage pulse, so that when a ~ 1.5 kV positive trigger pulse is imposed on the back of the ferroelectric cathode, a beam current pulse is obtained. The rise time of the beam current pulse, under appropriate trigger timing conditions, is much shorter than that of the secondary voltage.

The beam from the electron gun is used as an injector for a single stage X-band Traveling Wave Tube (TWT) amplifier. The disk loaded amplifier has 50 uniform irises and 11 tapered irises on each end. The inner and outer radii of the iris are 10 mm and 16.4 mm respectively, and the periodic spacing of the irises is 7 mm. This corresponds to the $\pi/2$ synchronous mode at the operating voltage and at a wave frequency of 9.0 GHz. The input waveguide at the beginning of the TWT is connected to an X-band magnetron which provides ~ 10 kW power into the TWT. A reflector mounted on the end of the anode is located at a distance equal to a $3/4$ wavelength of the TE_{11} mode, in order to reduce excitation of this mode.

At the end of the TWT, a coaxial mode converter/collector is used to separate the beam and amplified RF output³. The beam is dumped into the collector, in order to avoid re-acceleration of the beam electrons by the amplified RF. The amplified RF is efficiently mode converted from the TM_{01} mode of the slow wave structure into a TEM mode in the coaxial section. Measurement of the RF output power is made with an E field-probe mounted between the amplifier and the microwave absorber located at the end of the coaxial converter.

Experimental Results

Two sets of experiments have been conducted. The first is a study of the characteristics of the diode and beam dynamics. Optimum conditions for triggering the ferroelectric cathode, such as trigger voltage and timing, have been studied, and the longitudinal variation of the beam envelope has been measured with a 2-section Faraday cup. The second demonstrates the applicability of a

beam generated by a ferroelectric cathode as an electron source for a microwave tube. Details of the experimental results will be described in this section.

Beam Generation

An important feature of ferroelectric cathodes is that the electron emission is initiated by a trigger signal, that may be used to control the timing of the current with respect to the voltage pulse. The trigger timing and amplitude also may be used to control the current pulse shape and amplitude. However, the optimum conditions for applying the trigger, such as the timing and the magnitude, need to be determined. A series of experiment for testing the trigger conditions have been conducted. The trigger generator produces a pulse of 100 ns width and a voltage up to 3.2 kV. The trigger pulse is applied to the rear surface of the ferroelectric and is inductively decoupled from the main voltage pulse. Fig.3 shows the waveforms for the diode voltage and beam current as a function of the trigger timing.

Fig 3. Gun Voltage and Beam current as a function of the timing of the trigger pulse

Here $t=0$ is defined as the time when the diode voltage starts to rise. In the experiment, the peak diode voltage is kept at 450 kV and the applied trigger voltage is 2.1 kV. Varying the timing of the trigger pulse from 110 to 280 ns, the peak value of the beam current varies only between 200 to 210 A. However, changes of the pulse shape have been observed. The second curve, obtained by applying the trigger voltage at $t = 200$ ns, gives an approximately square pulse. The beam current is also observed for changing triggering voltages with a fixed trigger timing at 200 ns. Figure 4 shows the relation between the beam current and trigger voltage. The beam current is a rapid function

Fig. 4 Beam Current as a function of the Trigger Pulse Amplitude

of the trigger voltage once the threshold has been exceeded and until the trigger voltage exceeds 2 kV, when the beam current becomes largely independent of the trigger amplitude. The working trigger voltage was chosen to be 1.9 kV.

A Faraday cup has been used to determine the beam radius and its axial variation. The cup consists of two coaxial parts, an inner section which measures the beam current through a central aperture and the main section that measures the total beam current. The radius of the aperture is 2.38 mm. Assuming the radial profile of current density is uniform, the ratio of the two currents and the radius of the aperture allow a determination of the beam radius. By moving the Faraday cup in longitudinal direction, the axial variation of the beam radius can be obtained. The results are shown in Fig.5. The magnetic compression in the 2nd stage is significant, the beam radius being

Fig.5. Beam Radius as a function of the axial position. The dashed line shows EGUN simulations using the measured magnetic field profile. Radial variations of 0.3 mm are almost one order of magnitude smaller than those found in ref 5.

compressed from 6.5 mm to 4.1 mm. The difference between the measured beam radius and the design value as shown in Fig. 2 is caused by the difference of the magnetic field profile in two cases. The simulation result using actual magnetic field used is shown in Fig. 5. Good agreement with the experimental results has been found. The variation in the beam radius is less than 0.3 mm, and indicates that the beam is close to a matched condition.

Microwave Generation

The main purpose of this part of the experiment was to demonstrate that the electron beam generated from a ferroelectric cathode is suitable for high power microwave generation applications. The beam and TWT geometries have been indicated earlier. When the 200 A beam was used the TWT oscillated. As a result the beam current was limited by a 5 mm radius aperture to about 100 A. The remaining experiments were carried out using this beam. Fig. 6 shows the diode voltage, beam current, amplified microwave power and output from a heterodyne receiver in which part of the amplified signal is mixed with a reference signal from a local oscillator. The input microwave signal has a power of 18.7 kW at a frequency of 9.145 GHz. The peak of the output power is 5.9 MW, corresponding to a gain of 25 dB and an energy conversion efficiency of 13.1%. The heterodyne signal shows that the amplified signal is at a single frequency, which is equal to that of the input microwave signal.

Figure 6. Waveforms from the TWT amplifier

In Figure 7 we illustrate the frequency response of the single stage amplifier. Gain has been

Figure 7. Frequency response of X-band TWT amplifier.

observed over a frequency range of nearly 0.7 GHz from 8.9 to 9.5 GHz. Note that the amplifier has not been, in any way, optimized for output power or efficiency. The purpose here was solely to demonstrate that the beam quality was adequate for use in high power microwave applications.

In a separate experiment an effort was made to estimate the beam emittance directly from a measurement of the beam expansion following transport through a seven slit emittance screen. In this experiment the beam radius was increased by a reduction in the confining magnetic field. In zero order this process will not change the emittance since the increase in beam radius is accompanied by a cooling of the beam in the adiabatic magnetic field expansion region. The subsequent transverse expansion of the beamlets due to the beam temperature was measured using radio-chromic film. The estimated normalized emittance was found to be 10π mm.mrad. This

figure is consistent with the observation of gain in the X-band. The gain observation is however a poor test of the beam quality as the amplifier gain is expected to not be reduced (in X-band amplifiers) until the emittance is much larger than the estimated value reported here. However, above results indicate that the ferroelectric cathodes can be used as an electron source for a high power X-band TWT and that microwave amplification of ~30 dB to MW levels is possible.

At present no life time tests have been carried out on ferroelectric emitters. Limitations in the cathode life may be severe if back sputtering occurs from the anode of the gun. A well designed beam channel and dump will be essential for long life operation. The fact that ferroelectrics have been cycled through billions of switchings in memory chips offers an encouraging observation.

Conclusions.

We have shown that ferroelectric cathodes may be used in electron guns to produce beams suitable for high power microwave applications. Peak powers of about 6 MW were measured in X band. This is the first reported observation of high power microwave sources using ferroelectric cathodes.

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APPENDIX 3.

Notes on Performance of a Two-Stage 35 GHz, Ka Band Amplifier

As with our two-stage dielectric and disk-loaded X band TWT amplifier, the dielectric-loaded stage here is not required to have significant gain. It serves primarily as an input for the microwave power, initiating the bunching process on the electron beam. The power extraction then occurs in the second stage. As a result, the dielectric stage was shortened somewhat compared to the single-stage dielectric amplifier described above when it was joined with the disk-loaded stage.

A diagram showing the configuration of the amplifier is given in Fig. 1. The uniform region of the dielectric is 17.8 cm (7 in.) in length, and there are 2.5 cm (1 in.) tapers on each end. The inner and outer radii of the dielectric are again 4.76 mm (0.187 in.) and 6.35 mm (0.25 in.), respectively, as in the case of the single-stage dielectric amplifier discussed above. In the disk-loaded slow wave structure 70 uniform cells were used initially (this was later increased to 90) with 10 tapered cells on each end. The absorber at the beam entrance is the magnetic absorber mentioned in the previous section, the sever is comprised of 5 Kapton fins having lengths of 8.9 cm (3.5 in.), and the end absorber is a SiC tube with a shallow 1.3 cm (0.5 in.) taper inside.

Along with modifying the dielectric stage, the basic vacuum diode configuration was changed as an initial step toward improving beam quality. The beam quality or, in particular, the initial energy spread of the electrons in the beam driving the source plays a crucial role in determining the maximum power available for conversion. L. Schächter and J. A. Nation have discussed the importance of these factors for Ka band amplifiers in a recent paper [1]. The vacuum diode was originally in a "fringing-field" configuration, where the cathode emission surface was in a region at the end of the magnetic field solenoid where the field lines began to diverge. There was some evidence of beam scalloping and "cork-screwing" as the beam propagated along the length of the amplifier structure with this diode arrangement. It was therefore decided to work instead with a "field-immersed" cathode configuration for the diode, where electrons would then be emitted in a uniform region of the magnetic field. This configuration led to a drop in the beam current, but for initial experiments this drop was deemed acceptable. Particle-in-cell simulation of the diode with a cathode voltage of 850 ~ 900 kV predicted a beam current of 140 ~ 145 A; in practice, currents of 100 ~ 125 A are readily obtained.

A. Numerical Simulations of the Two-Stage Amplifier Configuration

Further numerical simulations were performed to obtain an estimate of the operation of the two amplifier stages working together. The beam current was reduced in these simulations to 100 A to reflect the recent changes in the electron beam diode. In order to reduce the run time for the simulations, the simulations were run in two parts: first, the simulation of the dielectric stage was run, and data for the electron beam and microwave fields at the exit end of the stage were saved to data files. Next, the simulation of the disk-loaded stage was run using the data from these files as input. The microwave fields

were artificially absorbed immediately at the input, representing the effect of the sever, thereby leaving only the bunched beam to propagate into the disk-loaded structure.

Figure 2 shows an illustration of the dielectric stage with the electron beam propagating through it, a plot of the axial momentum of the beam showing how the beam is bunched, and a plot of the net electromagnetic power along the axis of the stage. An input power of 5 kW was used in this simulation, and half of this power leaves the simulation at the left-hand boundary reflecting the presence of an absorber here in the experiment. As can be seen from the graph in Fig. 2b, the depth of modulation in the beam is relatively small, just 1.75 % of the unperturbed value. Figure 2c shows that there is some amplification of the RF input power; 45 ~ 50 kW are indicated in the region following the dielectric, representing a gain of approximately 10 dB for this stage. An FFT performed on a time plot of the power measured close to the right-hand boundary of the simulation (Fig. 2d) shows that most of the power is in the first harmonic with a small fraction (~ 7 %) being in the second harmonic.

Plots from a simulation of the second stage are shown in Fig. 3. Again the first part of the figure shows an illustration of the beam propagating through the structure, part (b) shows a plot of the axial momentum along the axis, and plot (c) shows the net electromagnetic power along the axis. From the way the momentum oscillations begin to curve upwards again in Fig. 3b after 20 cm, it is clear that the electron bunches have begun to reabsorb energy from the microwave fields. Figure 3c indicates that the electromagnetic power reaches ~ 12.6 MW in this stage. An FFT of the time history of the power measured near the end of this stage (Fig. 3d) indicates that a significant amount of the power is in the second harmonic.

While the plot in Fig. 3c shows a peak power in this stage in excess of 12 MW, the level of the extractable microwave power may be somewhat less. T. Davis in his Ph.D. dissertation [2] provides a useful method of determining the extractable RF power apart from the other components of power that may be reflected in the plot generated by the simulation in Fig. 3c. This method utilizes the relation

$$P_1 = \frac{2}{N\Delta t} F_2 \quad (1)$$

and the amplitude of the second harmonic as measured from the FFT in Fig. 3d. Here N is the number of FFT samples (not the number of time steps in the simulation, but the next highest power of 2), Δt is the time increment for each time step in the simulation, F_2 is the amplitude of the second harmonic, and P_1 is the average RF power that will be radiated or extracted from the amplifier stage. For the simulation of Fig. 3, $N = 65536$, $\Delta t = 2 \times 10^{-13}$, $F_2 = 4.8 \times 10^7$ W/GHz, and therefore $P_1 = 7.25$ MW. This power represents a gain of 31.6 dB over the original input power of 5 kW.

A second set of simulations of the dielectric and disk-loaded stages was run in which 10 % of the total beam energy was distributed in transverse components (radial and azimuthal). Plots from the simulation of the disk-loaded stage are shown in Fig. 4. The resulting beam emittance for this case is between 160 and 170 mm-mrad (Fig. 4c). Despite the higher beam emittance, however, there is not a significant drop in power.

Taking the amplitude of the second harmonic in Fig. 4e and again applying Eqn. (1), a power $P_1 = 6.88$ MW is obtained. The gain in this case is 31.4 dB.

By changing the way that power is coupled out of the end of the slow-wave structure some improvements in performance can be obtained. With the addition of a coaxial transition at the end of the slow wave structure, as shown in Fig. 5a, and as well as the reduction of the length of the disk-loaded structure to 65 cells, over-bunching of the electron beam can be prevented (Fig. 5b). Using Eqn. (1) and the amplitude of the second harmonic as shown in Fig. 5d the amount of power that can be radiated is now calculated to be up to 12.6 MW, resulting in a gain for the amplifier of 34.0 dB, a significant improvement over the first case.

B. Results of Experimental Investigation

With both the disk-loaded slow wave structure and the sever removed, several test shots were performed to check the operation of the dielectric stage of the amplifier alone. The tuning stub position and operating frequency ($\sim 35.1175 \pm 0.0025$ GHz) were chosen based upon measurements made with a network analyzer showing that most of the input RF power would be coupled into the TM_{01} mode for these parameters. Figure 6 shows the waveforms from E probes #3 and #4 (Fig. 1), which were left in place for these tests, with only the input RF power from the magnetron in the amplifier. This power level indicated here is approximately 2.7 kW, about half of that used in the simulations.

Figure 7 shows the probe waveforms, along with those for beam current and voltage, when the electron beam is also injected. As seen in Fig. 7, the E probe signal shapes are similar, though the amplitudes are slightly different. Both signals show an increase in power throughout the duration of the pulse, which is likely caused by the fact that the current pulse is not flat in this shot but is also increasing over its duration. The amplitudes at the ends of the pulses are within the range of powers predicted by the numerical simulations, 40 ~ 80 kW, even though the input power is down by half.

In Fig. 8 the current, voltage, and E probe waveforms are shown for a shot with the disk-loaded SWS and the sever joined with the dielectric stage. The voltage is essentially the same as in the previous case of Fig. 7, though current is about 20 % higher. Both E probe waveforms again have similar shapes, starting at a low power and climbing to a higher power, but their variation in time is not quite as smooth now. Despite the fact that there is a 13 dB difference in their relative attenuations with respect to the signal level obtained with the magnetron microwave pulse alone, these waveforms show approximately equal power levels due to the fact that the response of the two microwave diode detectors is rather different. (Note that these are 50 mV signals as opposed to the 20 mV signals shown in Fig. 6.) The peak powers indicated here are 1.9 MW for E Probe #3 and 2.2 MW for E Probe #4. The input microwave power was measured to be approximately 3 kW for this shot; taking these two peak power values, the amplifier gain is then found to be 28.0 dB and 28.6 dB. These values are very close to the gains predicted by the numerical simulations.

In an effort to increase the input microwave power from the magnetron source into the dielectric stage, the microwave absorber near the beam entrance to the amplifier (Fig. 1) was removed. The microwave power normally absorbed here was then reflected back

into the dielectric stage, effectively doubling the input power. After this change, it was necessary to adjust the tuning stub and the frequency of the input microwave power to maintain minimum coupling into the TE_{11} mode within the amplifier, and this calibration was accomplished with the network analyzer again. Figure 9 shows plots of current, voltage, and the E probe signals from a shot after this change was made. There is considerable improvement in the shapes of the E probe signals, however when comparing to a 20 mV magnetron-only signal (not shown) there seems to be a much lower gain in the amplifier output for this case. Unfortunately, at present calibrations of the microwave detectors for this microwave frequency (35.3 GHz) have not been performed, yet, so it is not possible to determine accurately the absolute power levels represented here.

Conclusions

Though the power levels have been modest, the results shown in Fig. 8 indicate that the TWT amplifier is operating at gains that are very close to those predicted by numerical simulations. Microwave pulse shapes are not very flat, but this feature is likely attributed to the fact that the current pulse is not flat. Thus, in order to obtain further improvements in operation the first step that is needed is to improve the current pulse shape. Increasing the level of the input microwave power by some means other than removing the absorber at the beam entrance to the amplifier seems to be another requirement for improving microwave pulse shape, as evidenced by the improvements seen in Fig. 9. Further increases in power levels then can likely be obtained by introducing a coaxial transition at the end of the disk-loaded structure, as predicted by the simulation results shown in Fig. 5, and by increasing the current level to 200+ A. Simulation results for a 200 A beam injected into the amplifier predict that power levels of up to 28 MW can then be obtained.

Detailed View of the TWT Amplifier:

Results From Simulation of Dielectric Stage of Amplifier:

Time 10.000 ns: PHASESPACE for all particles

PHASESPACE Plot 4

Remarks: EXPORT command used to record beam data for use in disk-loaded amplifier simulation.

Length of dielectric = 7 in.

Guiding B field 1.000 Tesla.

Beam I = 100. Amp, Beam Energy = 850000. Volts

Device: 35 GHz Dielectric Am
Run No: #5
File: 35GHz Diel-7.m2d
Author: Chris Grabowski
Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: Apr 15, 2000

Time: 22:41

Page: 96

Time 10.000 ns: PHASESPACE for all particles

PHASESPACE Plot 3

Remarks: EXPORT command used to record beam data for use in disk-loaded amplifier simulation.

Length of dielectric = 7 in.

Guiding B field 1.000 Tesla.

Beam I = 100. Amp, Beam Energy = 850000. Volts

Device: 35 GHz Dielectric Am
Run No: #5
File: 35GHz Diel-7.m2d
Author: Chris Grabowski
Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: Apr 15, 2000

Time: 22:41

Page: 95

Results From Simulation of Disk-Loaded Stage of Amplifier:

Time 10.000 ns: PHASESPACE for all particles

PHASESPACE Plot 3

Remarks: 70 cells in SWS, 1mm/1mm
IMPORT beam data from simulation of dielectric stage
with 7.0 in. dielectric.
Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
Run No: #3
File: 35disk.m2d
Author: Chris Grabowski
Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: Apr 17, 2000

Time: 00:19

Page: 114

Time 10.000 ns: PHASESPACE for all particles

PHASESPACE Plot 4

Remarks: 70 cells in SWS, 1mm/1mm
IMPORT beam data from simulation of dielectric stage
with 7.0 in. dielectric.
Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
Run No: #3
File: 35disk.m2d
Author: Chris Grabowski
Organization: High Voltage
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MAGIC2D

Version: March 1999

Date: Apr 17, 2000

Time: 00:19

Page: 115

Time 9.971 ns: Sz_NET AT 3.512E+10 Hz SPLITTER at SIMULATION_AREA

RANGE Plot 16, POYNTING SPLITTER
Line: (0.000m, 2.900mm) To (24.10cm, 2.900mm)
Temporal average: 56.885 ps
Remarks: 70 cells in SWS, 1mm/1mm
IMPORT beam data from simulation of dielectric stage
with 7.0 in. dielectric.
Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
Run No: #3
File: 35disk.m2d
Author: Chris Grabowski
Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: Apr 17,2000

Time: 00:19

Page: 108

Magnitude Of FFT Of S.DA at P_FLOW

Line: (23.60cm, 0.000m) To (23.60cm, 5.000mm)
Peaks (GHz):35.118,70.241, Df=100.00 MHz
Remarks: 70 cells in SWS, 1mm/1mm
IMPORT beam data from simulation of dielectric stage
with 7.0 in. dielectric.
Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
Run No: #3
File: 35disk.m2d
Author: Chris Grabowski
Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: Apr 17,2000

Time: 00:19

Page: 36

10 % of Beam Energy Distributed in Transverse Components:

Time 10.000 ns: PHASESPACE for all particles

PHASESPACE Plot 3

Remarks: 70 cells in SWS, 1mm/1mm

IMPCRT beam data from dielectric stage simulation #7.

Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A

Run No: #7

File: 35disk.m2d

Author: Chris Grabowski

Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: May 01, 2000

Time: 14:47

Page: 114

Time 10.000 ns: PHASESPACE for all particles

PHASESPACE Plot 4

Remarks: 70 cells in SWS, 1mm/1mm

IMPCRT beam data from dielectric stage simulation #7.

Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A

Run No: #7

File: 35disk.m2d

Author: Chris Grabowski

Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: May 01, 2000

Time: 14:47

Page: 115

Area: (1.000cm, 0.000m) To (2.000cm, 5.000mm)
 Remarks: 70 cells in SWS, 1mm/1mm
 IMPCRT beam data from dielectric stage simulation #7.
 Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
 Run No: #7
 File: 35disk.m2d
 Author: Chris Grabowski
 Organization: High Voltage
 Lab, Cornell University

MAGIC2D

Version: March 1999

Date: May 01, 2000

Time: 14:47

Page: 136

Time 9.971 ns: Sz_NET AT 3.512E+10 Hz SPLITTER at SIMULATION_AREA

RANGE Plot 16, POYNTING SPLITTER
 Line: (0.000m, 2.900mm) To (24.10cm, 2.900mm)
 Temporal average: 56.885 ps
 Remarks: 70 cells in SWS, 1mm/1mm
 IMPCRT beam data from dielectric stage simulation #7.
 Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
 Run No: #1
 File: 35disk.m2d
 Author: Chris Grabowski
 Organization: High Voltage
 Lab, Cornell University

MAGIC2D

Version: March 1999

Date: May 01,2000

Time: 14:47

Page: 106

Magnitude Of FFT Of S.DA at P_FLOW

Line: (23.60cm, 0.000m) To (23.60cm, 3.000mm)
 Peaks (GHz): 35.118, 70.241, Df=100.00 MHz
 Remarks: 70 cells in SWS, 1mm/1mm
 IMPCRT beam data from dielectric stage simulation #7.
 Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
 Run No: #1
 File: 35disk.m2d
 Author: Chris Grabowski
 Organization: High Voltage
 Lab, Cornell University

MAGIC2D

Version: March 1999

Date: May 01,2000

Time: 14:47

Page: 166

Coaxial Transition Introduced at End of Slow-Wave Structure, Number of Cells Reduced From 70 to 65:

Time 10.000 ns: PHASESPACE for all particles

PHASESPACE Plot 3

Remarks: 65 cells in SWS, 1mm/1mm
IMPCRT beam data from simulation of dielectric stage
with 7.0 in. dielectric. Include beam extractor now.
Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
Run No: #5
File: 35disk.m2d
Author: Chris Grabowski
Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: Apr 22, 2000

Time: 17:45

Page: 114

Time 10.000 ns: PHASESPACE for all particles

PHASESPACE Plot 4

Remarks: 65 cells in SWS, 1mm/1mm
IMPCRT beam data from simulation of dielectric stage
with 7.0 in. dielectric. Include beam extractor now.
Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
Run No: #5
File: 35disk.m2d
Author: Chris Grabowski
Organization: High Voltage
Lab, Cornell University

MAGIC2D

Version: March 1999

Date: Apr 22, 2000

Time: 17:45

Page: 115

Time 9.971 ns: Sz_NET AT 3.512E+10 Hz SPLITTER at SIMULATION_AREA

RANGE Plot: 16, POINTING SPLITTER
 Line: (0.000m, 2.900mm) To (23.10cm, 2.900mm)
 Temporal average: 56.885 ps
 Remarks: 65 cells in SWS, 1mm/1mm
 IMPCRT beam data from simulation of dielectric stage
 with 7.0 in. dielectric. Include beam extractor now.
 Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
 Run No: #5
 File: 35disk.m2d
 Author: Chris Grabowski
 Organization: High Voltage
 Lab, Cornell University

MAGIC2D Version: March 1999 Date: Apr 22, 2000 Time: 17:45 Page: 106

Magnitude Of FFT Of S.DA at P_FLOW

Line: (22.60cm, 3.300mm) To (22.60cm, 5.000mm)
 Peaks (GHz): 70.225, DF=100.00 MHz
 Remarks: 65 cells in SWS, 1mm/1mm
 IMPCRT beam data from simulation of dielectric stage
 with 7.0 in. dielectric. Include beam extractor now.
 Guiding B field 1.000 Tesla.

Device: 35 GHz Disk-Loaded A
 Run No: #5
 File: 35disk.m2d
 Author: Chris Grabowski
 Organization: High Voltage
 Lab, Cornell University

MAGIC2D Version: March 1999 Date: Apr 22, 2000 Time: 17:45 Page: 167

Magnetron Pulse Only In Amplifier

Operation of Dielectric Stage Only

Performance of Two-Stage Amplifier

Performance of Two-Stage Amplifier

(Absorber at Beam Entrance to Amplifier Removed)