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COLLECTIVE ACCELERATION OF ELECTRONS AND IONS IN A
HIGH CURRENT RELATIVISTIC ELECTRON BEAM

PROGRESS REPORT
ON
CONTRACT DE-AC02-80ER10569

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Introduction

This report summarizes work carried out during the current contract period on contract # DE-AC02-80ER10569. The report is divided into 4 sections, the first of which summarizes changes in the available laboratory facilities. In the second section we report on the experimental program and in the third section we summarize theoretical progress. We then provide a brief account of the immediate directions for our current research. The report concludes with a list of publications and conference presentations arising from this research. A subset of these publications are appended to the proposal to provide further information.

1. Laboratory Facilities

Electron Beam Machines: The modified ETA module is now in regular operation at a voltage of about 450 kV and at an impedance of 40 Ohms. The system appears to run reliably. Our annular electron beam high power microwave amplifier experiment runs on this facility. More detail of the experimental configuration and experimentation will be found later in this report.

We have modified one of our other electron beam machines to run in negative polarity instead of the positive polarity used in the last several years. This machine, which can operate at voltages up to 1.1 MV and has a 63 Ohm impedance, will be used for high power microwave and accelerator experiments. It is particularly well suited to new diode design experimentation, such as might be needed if we employ Ferroelectric cathodes in our experiments, because we have an inductively isolated access to the cathode through the ferrite cores driving the machine. In addition we have wound new field coils to confine the propagating beam, and are developing a new experimental area for the machine which will include a microwave absorber screened area. These modifications should be complete at the end of January 1991.

As part of our program we have initiated a new activity on ferroelectric emitters. These show promise as low emittance, high current, electron sources. A test bed has been constructed for these experiments which includes a basic vacuum

station and a 2.5 kV 100 nsec. pulser to reverse the polarization of the ferrite cathodes. This facility and results from the experiments which were recently initiated will be reported later in the report.

Diagnostic Facilities: The strong emphasis on microwave research as applied to accelerators in our laboratory has led to the need for a phase detector system. This is now in use and can measure the relative phase between two X band microwave signals with an accuracy of 8° .

The Laboratory's data acquisition system, based on four 7912AD Tektronix digitizers can now be controlled using a Microvax II, running under the Unix operating system. The acquisition software and graphics routines have been completed and the entire system has been tested on an operating experiment. The system has a number of operating modes designed with our particular experimental requirements in mind. In single shot mode the data is acquired, the resulting waveforms are graphed to a terminal screen and also stored automatically on disk. The software allows immediate waveform analysis including differentiation, integration, Fourier transforms and pulse height and width measurements. In repetitive mode the data from a sequence of shots is acquired and stored on disk at a rate of approximately 1 Hz. We can then display the waveforms from each separate shot or perform an averaging which will include the shot-to-shot variations within the run. The acquisition rate can be increased by modifying sections of the code, if our experimental requirements call for this.

We are currently installing a fiber optic ethernet connection between the experiment screen room and our main terminal area. This should be completed by the end of the current year, at which time we will move the Microvax system to the screen room, where it will be employed as the digitizer controller. The ethernet link will provide full-time access to the experimental data by all research personnel at the Laboratory.

2. Experimental Program

Traveling Wave Tube Amplifiers: Work has continued on the development of traveling wave tube amplifiers. A paper was published on June describing results

on a single stage device and a letter paper and a regular paper have been submitted for publication describing a two stage amplifier system. These papers are appended to this report and we shall only present a few highlights from our results here.

Our single stage device operated at 8.76 GHz, at an output power level of 100MW and an efficiency of 11%, with a very narrow bandwidth of about 20 MHz. During the current year we have extended this regime to include a two stage severed amplifier which permitted an increase in the extracted power to over 400MW, at an efficiency in excess of 45%. Unfortunately, this increase in power has been accompanied by the onset of sidebands. The presence of the sidebands is shown by heterodyning the output signal with that of a klystron as a local oscillator. Data comparing the outputs from the single stage device and the severed amplifier at comparable electron beam power is also shown in figure 1. It should be noted that similar results are obtained from the single stage device at power levels in excess of 70 MW. The microwave power at the center frequency has however increased to about 210 MW at 8.76 GHz with an amplified signal efficiency of 22%. Techniques were developed to measure the power in each of the sidebands and the results obtained are shown in figure 2. We will present an invited paper at the IEDM meeting in San Francisco in December 1990 on this topic.

As part of the requirements for the development of an rf source suitable for us in an accelerator it was necessary to demonstrate the wave phase stability. This has been accomplished, to at least a minimal degree, in the last year using an Anaren phase discriminator. In this device the amplified (i.e. 100 MW) microwave output is sampled and compared with the output from a low power klystron. The output from the device, after numerical manipulation, gives a direct measure of the phase angle between the two sources. A typical output, at the 70 MW level, is shown in figure 3, which demonstrates that the wave is phase stable to better than the $\pm 8^\circ$ accuracy of the diagnostic. Substantially more detail is presented in the appended papers.

Coaxial Beam Amplifiers: During the past year we have continued work on the design and experimentation with high power X-band coaxial amplifiers as part of the program to develop ultra-high power microwave sources for use in future

Fig. 2 Comparison of the gain as a function of beam current for the single stage 22 period amplifier with that of the severed amplifier.

Fig. 2 Relative power distribution between the center (8.76 GHz) frequency and the adjacent sidebands as a function of the beam current. Data was not obtained at beam currents below the peak in the gain curve.

Fig.3 Measured phase angle between the single stage amplifier output and the signal from an equal frequency reference source. The zero is arbitrary. The output phase is constant within the limits set by the accuracy of the measurement, i.e. $\pm 8^\circ$

linear colliders. These amplifiers, which employ a large diameter annular beam propagating between the inner and outer conductors of a coaxial drift tube, can overcome the limits of standard pencil beam amplifiers by markedly increasing the beam current available and by reducing the surface field levels which determine r.f. breakdown. Most high power pencil beam amplifiers (relativistic klystrons, traveling wave amplifiers) are space charge or current density limited to beams of 1-2 kA, while even a 2 mm thin annular beam at our design diameter of 9 cm has yielded currents over 7 kA. By varying the separation distance between drift tube conductors, we can still operate without competing TM modes (a klystron geometry) or with only a single TM mode (a traveling wave geometry). This eliminates the frequency limitations arising in the klystron geometry used by Friedman and the SLAC/LLNL groups. Recently Friedman has published an internal NRL memorandum which also points out this possibility¹. A TWT version using the annular beam geometry was developed at Cornell and reported in 1970².

The complexity with a coaxial system arises due to mode competition from the normal transmission line mode (TEM) as well as several TE modes which can propagate in large diameter coaxial systems (Note however that there will only be one axisymmetric TM mode). The TE and TEM modes do not interact to first order with an axially bunched beam but are invariably coupled to cavity or traveling wave section fields through apertures or perturbations. We are developing a further understanding of the effects of these lower order modes on our device operation through experimental and simulation results.

During the past year we have fabricated the coaxial amplifier components and run a series of beam and cavity experiments as well as obtained simulation and modelling results for the system. During the rest of the current year and during the next year experiments will be performed to characterize the annular amplifier operation. All of the experiments to date have been run on our newly commissioned ETA module, capable of 500 kV with a source impedance of

¹J. Krall, M. Friedman, Y.Y. Lau and V. Serlin, NRL Memorandum 6570, Nov.20 1990. Simulation studies of a Klystron like Amplifier operating in the 10-100 Gw regime

² J. A. Nation Appl. Phys. Letts. 17, 491, (1970). On the coupling of a High Current Relativistic Electron Beam to a Slow Wave Structure.

nominally 40 ohms. Although repetition rates of 1 Hz with this module are possible, we are currently limited to single shot techniques by the large diameter bore magnetic coil system needed for these experiments.

The first series of experiments were performed to develop a beam capable of satisfying our amplifier requirements. We fabricated and tested a number of field emission annular beam cathodes, all fully immersed in a solenoidal guiding field of about 1 Tesla. Because of the high impedance source, careful design of the diode to avoid electron loss was necessary. Equally important, considerations were given to reducing cathode shank emission (leading to thick beams with high transverse temperature) and creating azimuthally uniform emission. An excellent configuration for these requirements was found to be a conical brass mount with a graphite emitting tip. An equipotential plot for this geometry is shown in figure 4. The conical shape localizes emission to the graphite tip, a good material for uniform turn-on over large areas. A sample damage pattern from this cathode is shown in figure 5. Note that the thermal paper used has a response which is highly non linear and that only the gross characteristics are significant. Beam current and beam damage diagnostics were placed after a meter long section of drift space, indicating stable propagation along the coil system. Typical beam voltage and current waveforms (monitored using a resistive divider and inner and outer conductor Rogowski coils, respectively) are shown in figure 6. We are currently operating the diode to yield beams with peak energies of 420 keV and currents of 7.2 kA. Even with a rather modest pulse power source, this is a factor of three increase in beam power over most X-band pencil beam amplifiers (approximately 1 MeV, 1 kA) and is adequate to demonstrate the potential of the annular beam geometry for the controlled generation of microwave radiation at the 10^{10} watt level. To achieve these power levels will only require comparable conversion efficiencies and power densities to those already accomplished in our present pencil beam geometry. Operation at this level may relax present constraints on the cost and efficiency of the induction linacs used to drive the rf sources.

A current series of experiments is now attempting to characterize beam-cavity physics in the coaxial geometry. All of our current amplifier designs require initial beam modulation from an input cavity which is driven by an external source. The beam modulation will be amplified in subsequent cavities or traveling

Annular beam diode

Figure 4. Equipotential contours for the conical cathode geometry. Conductors are thickened lines. The entire region is uniformly immersed in a magnetic guiding field of 1 Tesla.

Figure 5. A beam pattern using thermal damage paper. The target was placed one meter downstream of the diode. The gaps in the pattern are due to three struts which support and center the inner conductor.

Figure 6. A typical set of beam voltage (above) and beam current (below) waveforms. The total current is measured by subtracting the outer and inner Rogowski signals.

wave sections. For this purpose we designed a $5/2$ wavelength toroidal TEM coaxial cavity as described in the last contract report. A cold test of the resonances in this cavity displayed many more modes than anticipated (see figure 7). These modes are most likely due to excitation of higher order azimuthal TE cavity modes, but make it difficult to identify the frequency of the design mode using simple microwave test bench methods. To identify the mode of interest experimentally, we are now driving the cavity with the actual beam and measuring the resulting frequency spectrum using dispersive line and heterodyning techniques. The dominant frequency is most likely the design mode, since this couples most effectively to the beam. After these experiments, we will be able to drive the cavity using an external source to impose the initial beam modulation.

The use of the 2-1/2 dimensional particle-in-cell code MAGIC has allowed us to simulate coaxial beam-cavity interactions. By using a beam that matches the experimental conditions and by driving a cavity at the simulation resonance we have proven that modulation can be imposed on the beam. Figure 8 shows the geometry and results of a simple simulation. In comparing these to pencil beam klystron simulations, we have also determined that the modulation process is much less efficient in the coaxial geometry. Therefore, it may not be possible to use a simple series of discrete cavities to approach high power levels. We are currently quantifying these results to determine their implications and improve the system design.

Finally, the complexity and efficiencies of simple cavity operation (as in a coaxial klystron) are proving to us that significant gain of the amplifiers is necessary to raise the system interaction efficiencies to interesting levels. At this stage it is not obvious that sufficient gain will be achieved without longer interaction regions than those use in existing relativistic klystrons or traveling wave tube amplifiers. Calculations during the previous year have determined that although we could design several interactions with singly corrugated coaxial structures, these interactions were dominated by substantial radial field energy. It is probably necessary to minimize these radial fields at the beam location by using a doubly corrugated system. This is most easily accomplished using a dielectric slow wave structure. The geometries of different traveling wave structures are shown in figure 9. This development of a stable coaxial traveling wave interaction will

Figure 7. Network analyzer sweep trace of resonant modes in cavity.

Figure 8. The geometry of coaxial cavity MAGIC simulations (above) with the cavity driven at resonance. An azimuthal magnetic field diagnostic in the simulation (below), taken along the drift tube wall, demonstrates coherent bunch formation at the frequency of cavity resonance.

Figure 3. Geometries of coaxial traveling wave structures. Modes in the singly corrugated structure (top) tend to have excessive radial fields at the beam location. It may be possible to minimize these fields using a doubly corrugated structure (center) or more likely, due to manufacturing considerations, a symmetric dielectric structure (bottom).

consume much of the effort in the immediate future.

Ferroelectric Ceramics

Sections of the particle accelerator community have recently shown interest in the use of ferroelectric materials as electron beam sources. Emitted electron current densities of several Amps per sq. cm³ to several hundred Amps per sq. cm.⁴ have been reported. These materials may offer electron beam sources with current densities ~ 1 kA/cm² that will be well suited to high current, high repetition rate operation with 50 - 100 nsec pulses and also, at lower currents provide an interesting low emittance electron source.

Electron emission has been achieved from a variety of ferroelectric ceramics, with much work being done with lead-zirconium-titanate (PZT) and lead-lanthanum-zirconium-titanate (PLZT). The emission occurs when surface charge on the material is released by a rapid change in the spontaneous polarization, P_s . The polarization in these materials is achieved by a poling process. This usually involves heating the material in the presence of an applied electric field and then allowing the sample to cool to room temperature while maintaining the applied field. Non-permanent changes in P_s can be achieved by applying a voltage pulse across electrodes plated onto the ferroelectric sample. One of these electrodes has an etched grid pattern to provide the emission region. Typical values of P_s are in the tens of $\mu\text{C}/\text{cm}^2$ corresponding to surface electron densities of 10^{13} - 10^{14} /cm². The exact emission characteristics of these materials depend strongly on their composition, treatment history and the external circuit to which they are connected.

We have measured the D-E characteristics of a number of ferroelectric materials using a modified Sawyer-Tower⁵ circuit shown in figure 10. A typical curve for PZT-5H is shown in figure 11. The value of P_s , the polarization in the

³ H. Gundel, H. Riege et al., *Ferroelectrics* 100, 1 (1989).

⁴ A. Sh. Airapetov et al., *Beams 90 Conference*, Novosibirsk (1990), To be published.

⁵ C. B. Sawyer and C. H. Tower, *Phys. Rev.* 35, 269 (1930).

Figure 1C Modified Sawyer-Tower circuit used to measure P-E characteristics of ferroelectric (FE) samples.

Figure 1) Oscilloscope trace of P-E curve for PZT-5H. Applied field is displayed on X plates, charge on sample is displayed on Y plates. Horizontal scale is 1872 V/div, vertical scale 130 V/div.

sample with no applied field, is $20 \mu\text{C}/\text{cm}^2$ and the coercive field, E_c , the minimum field required to reverse the polarization direction, is $4.5 \text{ kV}/\text{cm}$. It should be noted that the shape of this curve and the values of P_s and E_c are dependent on the sample temperature.

We are studying emission from a number of different PZT materials using the experimental set-up shown in figure 12. The 1Ω transmission line generates a $1-2 \text{ kV}$, 100 ns pulse. Electron emission is measured with a carbon Faraday cup which can be operated biased or un-biased. Traces of the voltage to switch the ferroelectric and the emitted electron pulse are shown in figure 13. In the preliminary experiments carried out to date we have succeeded in extracting electron current densities of about $10 \text{ A}/\text{cm}^2$. This corresponds to about 40 times the space charge limited current density for a simple thermionic space charge limited emission and is probably due to electron emission with an initial energy in the range of 2 keV . More information is needed on these sources to characterize their emission characteristics and to understand the emission process adequately.

Our experiments characterizing the electron emission from these materials as a function of such parameters as applied pulse length, polarity and magnitude are continuing. We are planning to add a separate grid between the ferroelectric emitter and the Faraday cup that can be biased to give information about the energies of the emitted electrons.

These materials appear to offer an electron beam source that would be extremely useful in microwave generation research. In particular, they are well suited to high repetition rate operation as their "recovery time", needed to re-establish charge distribution, is on a submicrosecond time-scale ⁶. In addition it should be possible to produce a variety of beam profiles designed for specific applications by etching the required grid pattern onto the appropriate electrode.

3. Theoretical Program

Microwave Program: Theoretical modelling has shed significant light on the processes involved in determining the bandwidth in the amplifier systems. Much of

⁶ H. Riege. CERN-PS-NOTE 89-15 (AR) (1989).

Figure 12. Schematic of experimental set-up showing sample mounted at Blumlein output. Carbon collector position and bias voltage are adjustable.

Figure 13. Digitizer traces showing applied pulse voltage and collector current for a PZT-2M sample. Collector bias voltage, with 20 nF capacitor: 150 V; collector distance: 1.25 mm.

this work has been directed by Levi Schacter, a visiting scientist, from the Technion. Dr Schacter will be working with us for a three year period on problems related to the DoE program. His work is partially funded by the supplemental funding provided during the latter two years of the current contract. We summarize below results from this work under four topic headings:

- [1] Gain and Interaction Buildup
- [2] bandwidth Characteristics and
- [3] Severed Amplifier Characteristics
- [4] Simulation Data

[1] Gain and Interaction Buildup (Single Stage Device): The amplifier gain in conventional TWT's may be expressed in the form

$$\text{Gain} = -9.54 + 8.69 q_i d$$

where q_i is the coupling coefficient and is proportional to the beam current to the one third power and d is the effective interaction length. We use this expression to compute the gain experimentally which we compare with calculations following 64 clusters of particles with a 5% energy spread and uniformly distributed over all phases of the electromagnetic wave. The particles satisfy a steady state energy equation

$$\frac{d}{dz} \gamma_i(\bar{z}) = \frac{1}{2} [j a(\bar{z}) e^{j\chi_i} + \text{c.c.}]$$

where $a(\bar{z}) = e E_z(\bar{z}) d / m c^2$

and d is the structure length and E is the slowly varying electric field amplitude and χ_i represents the phase of the electron relative to the wave. The wave equation completes the equations needed to describe the particle motion. In this notation the slowly varying field amplitude is related to the coupling coefficient α and the particle phase relative to the wave by

$$\frac{d}{dz} a(\bar{z}) = j \alpha \langle e^{-j \chi_i} \rangle$$

The solution to these equations is shown in figure 14 at various locations along the length of the interaction cell. The particle energy for up to half of the particles has grown dramatically with peak values of γ approaching 3.5 while the other half of the particles have lost energy with a γ of about 1.75. Over 20 % of the tube length has been used in bunching the beam. The resultant gain is shown in figure 15 as a function of length. The bunching length needed before gain starts is clearly shown. In addition we note that although the particles gain and lose substantial amounts of energy the average value of γ only changes to reflect the system interaction efficiency. Finally we note that the gain after bunching has developed does closely match the Pierce calculation. We therefore feel that we have a good understanding of the gain process and that we have accounted for the apparent discrepancies reported earlier with the Pierce formalism. It is surprising that the Pierce description yields such a good agreement with gains calculated following the particles through the structure since they form two beamlets with substantially different energies to those of the original beam. The agreement apparently occurs since the average energy is the parameter which determines the total gain.

Severed Amplifier: We have carried out similar calculations for the severed amplifier modifying the model to allow for absorption of the incident EM wave in the sever. In the second section the EM mode is reconstructed and starts to grow again with the bunches. Figures 16 and 17 show the calculated gain and the loss of electron energy in traversing the second amplifier stage for beam currents of 850 and 950 Amperes. Calculated gains of over 30 dB are indicated and saturation is apparent in both cases. The parameter $\Delta\gamma$ measures the rms spread in the electron energy as a function of position and is considerably larger than the change in the average value of γ , the electron energy. Note once again that the Pierce calculation gives a reasonable description of the gain as a function of length once the initial bunching is complete.

Fig.14 Phase space distribution at different points along the amplifier.

Fig.15 The gain developing in space. After a short build-up region the gain (in dB) increases linearly. The dashed line represents the gain as calculated using Pierce's TWT theory for the same parameters. The average energy of the electrons barely varies whereas there spread increases significantly.

Fig.16 The variation in space of the gain in the two stage amplifier. The sever is idealized here by assuming complete absorption in an infinitesimally small region of space. In the first section, the gain behaves exactly as described for the one stage amplifier. In the second stage the EM mode is reconstructed after being absorbed in the sever section. At 850A of current this simulation indicates that saturation occurs somewhat after the middle of the second stage.

Fig.17 Increasing the current to 950 the saturation in the second stage occurs somewhat before the middle.

[2] Bandwidth Characteristics (Single Stage Device): We attribute the very narrow bandwidth observed in the single stage device to the transmission characteristics of the structure. There is a slight mismatch between the rippled wall amplifier impedance and that of the uniform guide sections. This is impossible to avoid since, in the amplifier region, the dispersion relation is periodic in the wave number and is single valued in the uniform guide. In addition the gain per period is large and the structure is short so that transmission peaks in the structure are widely spread in comparison with those in conventional devices which typically have lengths (in structure periods) an order of magnitude greater than those used in these experiments. The number of peaks in the transmission coefficient between $k = 0$ and $k = \pi/l$, where l is the periodic length is equal to the number of ripple periods in the amplifier. We have previously reported bandwidth narrowing in the presence of the beam in calculations carried out with a dielectric loaded Cerenkov amplifier. The gain-bandwidth product was found to be constant. The process described in that report holds true for any amplifier in which there is reflection from the ends of the device. In the case of the severed amplifier the transmission coefficient for the complete system is dominated by the transmission coefficient for the sever and the peaks in the transmission coefficient do not occur. In this regime the gain-bandwidth curve reverts to the form expected using conventional TWT theory.

We have modelled the amplifier section as a transmission line with an impedance Z_s determined by the effective dielectric constant at the wave frequency. The amplifier is terminated by uniform guide sections with impedance Z_f . In the transmission line model we compute the transmission coefficient into the uniform output guide to be

$$\tau_{\text{cold}} = \frac{4 Z_f Z_s}{(Z_f + Z_s)^2 e^{j k_s d} - (Z_f - Z_s)^2 e^{-j k_s d}}$$

This is plotted in figure 18. The peaks correspond to constructive interference between the incident and the reflected waves. We define the cold bandwidth as the

Fig.18.a The transmission coefficient as a function of frequency. The extrema result from an interference of the two waves which are propagating in the slow wave structure. The bandwidth is the frequency range in which the transmission coefficient reaches half of its peak value.

Fig.18.b The transmission coefficient as a function of frequency with the beam present. The height of the peaks is affected by the gain but their separation is not significantly changed. The effective bandwidth is smaller by the same amount the peak of the transmission coefficient has been increased by the interaction.

distance between points 3 dB down from the peak value or, if the valleys are not 3 dB down by the frequency separation of the valleys. This separation is given by the group velocity of the structure divided by twice the length of the interaction region. In the presence of the beam the transmission coefficient is modified to yield

$$|\tau| \approx \frac{4 Z_f Z_s \frac{1}{3} e^{\text{Im}(q) d}}{(Z_f + Z_s)^2 - (Z_f - Z_s)^2 \frac{1}{3} e^{\text{Im}(q) d}}$$

and, for the active device, the bandwidth becomes

$$(\Delta f) = (\Delta f)_{\text{cold}} 10^{-\frac{\text{gain(dB)}}{20}}$$

A comparison is made between the predictions above and the experimental data and is shown in figure 19. The agreement is satisfactory considering that the theory does not include tapered sections in the amplifier

Severed Structure: In this situation the bandwidth is controlled by the sever, which has a high insertion impedance. Alternatively we might state that in either section of the amplifier one of the waves is absorbed in the sever (ideally) and hence there is no cavity effect to cause the structure in the frequency response curve. The bandwidth is then determined by the interaction between the beam and the structure and the standard gain result is recovered.

[3] Sidebands: "Sidebands" have been observed experimentally in both the severed amplifier and, at sufficiently high output microwave powers, in the single stage device. Simulation shows a similar phenomenon in long (20 nsec) runs. The very large spread in the electron momentum found in the simulations and in the analytic theory may be responsible for the "sideband" phenomenon. The fact that

- Experiment:

$$(\Delta f)_{act,11} \simeq 18MHz$$

$$(\Delta f)_{act,22} \simeq 14MHz$$

- Theory:

$$(\Delta f)_{cold,11} \simeq 234MHz$$

$$(\Delta f)_{cold,22} \simeq 122MHz$$

$$(\Delta f)_{act,11} \simeq 30MHz$$

$$(\Delta f)_{act,11} \simeq 11MHz$$

Fig.19 The bandwidth measured in two different experiments with 11 and 22 periods structure, is compared with the theoretical predictions.

the sidebands are not symmetrically located with respect to the center frequency, and the fact that the gain is still increasing linearly with structure length implies that the sidebands are not due to particle trapping. Particles with energies greater than the injected energy can cause wave growth at lower frequencies than the 8.76 GHz center frequency, whereas the lower energy particles may interact with higher frequency transmission peaks in the TM_{01} passband of the structure. We expect to find greater structure on the high frequency side of the center frequency, since the electron velocity is bounded in the narrow range between the injection velocity and the speed of light. The preferred frequencies will match the peaks in the transmission peaks described earlier for the beam loaded structure. Note that they are asymmetrically located with respect to the center frequency and their frequencies will be weakly dependent on the beam loading i.e. the beam current. The sidebands are especially pronounced in the severed amplifier due to the high gain and the fact that the electromagnetic wave must be reconstructed from the electron momentum spectrum, which is preserved in transit through the sever. The spread in electron energy then allows radiation to grow from noise at the preferred frequencies for the amplifier. For these reasons, namely the relatively short amplifier length and the small but finite reflection coefficient at the amplifier ends, we expect the sideband phenomenon to be much more important in high current, high power TWTs than in conventional low power long conventional devices. We speculate that the phenomenon could be reduced by use of higher energy electron beams and longer structures with weaker beam coupling to the structure.

We have modelled this interaction using the previously developed interaction development of the wave as a starting point. We assume that the EM wave is absorbed in the sever and is reconstructed from the bunched beam in the second amplifier section. We represent the wave input to the second stage from the incoherent addition of the radiation of each electron in the amplifier. The frequency is determined from the intersection of the beam line with the dispersion relation and the amplitude found from the electron distribution calculated previously. The input signal computed in this manner is shown in figure 20 and is denoted by U . We then analyze the wave growth in the second stage of the amplifier using a transmission line model similar to that described above. In this

Fig.20 The normalized induced noise is amplified. The interference of the two waves in the slow wave structure cause to a "selection" of frequencies. The peaks correspond to a constructive interference. The asymmetry of the peaks relative to the central frequency is apparent.

case we treat the amplifier as shown in figure 21 and represent the impedances of each section by Z_s , Z_{se} , and Z_t respectively where Z_s is the impedance of the structure, Z_{se} the (imaginary) impedance of the severed section and Z_t the impedance of the output taper which we approximate at the geometric mean of the structure impedance and that of the output section of guide. Using this notation we find

$$\tau \approx \frac{2 Z_s Z_t U e^{-j\Gamma d}}{e^{-jk_s d} e^{-j\Gamma d} (Z_s - Z_{se}) (Z_t - Z_s) + e^{jk_s d} (Z_s + Z_{se}) (Z_t + Z_s)}$$

where

$$e^{-j\Gamma d} \approx \frac{1}{3} e^{-jqd}$$

and Γ represents the effective growth of the wave in the structure and q is the complex wavevector. The output waveform given by the above relations is shown in figure 20 for an 850 ampere beam. The asymmetry in the output waveform is apparent. Although the details of the output are probably model dependent the basic concept probably gives a reasonable account of the sideband development.

[4] Simulation Data: We have during the past year obtained access to the 2 1/2 dimensional MAGIC code from MRC. The code has been made available through a program sponsored by the AFOSR. The code has been used to model microwave generation processes as described below.

Data has been obtained using the MAGIC code on the performance of single stage amplifiers. Two configurations have been examined, one with a twenty period structure and the other with a thirty period structure. In both cases a short input and output uniform guide is connected to the rippled wall amplifier. Note, however, that in these simulations no taper was used to match the slow wave structure to the uniform section of the guide. The ripples matched those used experimentally as closely as possible, within the limits of the constraints of the

Fig.21 Schematic description of the model used to simulate the output from the second stage. The sever and the termination are represented by uniform (but different) waveguides. The induced noise is represented as a source at the input of the second stage.

code. The microwave characteristics of ripple wall structures are very sensitive to details in the boundary conditions. As a result of this the interaction with an 850 keV electron beam was found to develop at 8.1 GHz instead of the 8.76 GHz measured experimentally. The dominant frequency was identified by examining the frequency spectrum which developed from noise. Amplification at other frequencies in the range 7.9 to 9.0 GHz was substantially lower than that found at the 8.1 GHz frequency used in the runs reported below. In the data to be presented we injected a 6 mm diameter, 850 kV, 1kA electron beam into the device. A TM wave is injected from the left boundary at the same time as the beam. Both the beam current and the rf wave have 1 nsec rise times. The injected microwave power corresponds to approximately 175 kW, based on the code output from the uniform section prior to the amplifier. Output powers of about 175 MW are recorded from the thirty period structure corresponding to tube gains of about 30 dB.

Fig 22 shows the output from the code for the radial electric field at the input, after 12 periods of the longer structure and at the output section of the amplifier. The field is measured just outside the beam radius. The wave has a well defined frequency of 8.1 GHz. The offset in the radial electric field signal indicates the DC electric field due to the unneutralized electron beam. Initially the modulation produced by the injected wave leads to a 10 % modulation which rises to 100 % at the output of the amplifier. The FFT of the output signal peaks at the frequency of the injected wave but shows about a 20 % broadening in the width of the frequency spectrum. No other fine structure is apparent in the spectrum. In fig 23 we show the momentum spectrum of the electrons measured as a function of position at the end of a 3.5 nsec simulation run. Two features are apparent in the data. Firstly there is a substantial spread in the electron momentum (measured as γv) corresponding to particles with energies ranging from 125 keV to 1.85 MeV with many of the particles clustered at the extremes in the electron energy. The average electron energy however remains close to the injected energy of 850 keV. In spite of this wide range of electron energies the gain is found to still increase linearly with the amplifier length at a rate of about 1.2 dB per structure period with little evidence of saturation apparent. The second feature is the perturbation in the momentum spectrum found close to the input of the tube. We identify this as

Fig. 22 Simulation output showing the radial electric field just exterior to the beam at three axial positions, at each end of the amplifier and (middle frame) 12 periods into the 30 period amplifier. The offset indicates the quasi static radial electric field due to the beam.

Fig. 23 Electron momentum (γv) as a function of position in the 30 period amplifier. About half the electrons have acquired almost 1 MeV while the other half have lost about 0.7 MeV. The average energy has not changed significantly from its initial value of 0.85 MeV.

being due to the reflected power from the output end of the amplifier. The effect is small due to the length of the run and because of the relatively small value of the reflection coefficient at the tube output.

Finally we show in fig 24 a plot of the FFT of the axial electric field in the 20 period structure. In this case we have increased the time step and increased the number of time steps from 14000 to 20000 to ensure adequate resolution in the frequency spectrum. The spectrum shows structure beyond that found in the earlier data with the 30 period device (which had an adequate number of time steps to obtain a good frequency resolution) but extending over only 3.5 nsec instead of the 20 nsec in this run. In addition, but not illustrated here, the particle momentum and wave electric field profiles as a function of position no longer clearly show the exponential growth reported earlier. There is sufficient time in the run for reflected waves to propagate through the structure several times and the effects of the reflections on the wave growth control the spectrum. i.e. we are seeing "sidebands" corresponding to the peaks in the transmission spectrum of the structure. Note that although the simulation and experimental conditions are somewhat different i.e. there are no input and output tapers, the basic physics of the interaction is maintained. The frequency structure appears to be due to the finite length effects and by impedance mismatch effects between the rippled wall and uniform guide sections. The peak in the spectrum shown in figure 24 appears to be controlled by the transmission peaks in the unloaded short structure microwave transmission characteristics. The strong agreement between these results and those from the analytic theory and experiments lend credence to the models used.

Upper Hybrid Waves

We initiated an experimental activity about 2 1/2 years ago to excite the upper hybrid mode wave on a relativistic electron beam. The purpose was to accelerate electrons directly in the wave without conversion of the wave to a radiative mode and then using it to energize a slow wave structure. A particularly appealing aspect of the wave was the fact that the wave group and phase velocities were both equal to the speed of light and that no nonuniform or slow wave structures were necessary to support the wave. This effort was not successful at that

Fig. 24. FFT of the radial electric field in 3.5 and 20 nsec simulations. The "sideband" appearance is due to the amplification of noise at discrete frequencies corresponding to the frequencies at which we have peaks in the transmission coefficient for the structure.

time and further investigation was deferred until after theoretical analysis of the mode was more advanced. We now report on that investigation. The wave has now been identified and been propagated in a pipe. In the linear regime investigated to date the solution is robust and shows the desired characteristics. We now summarize these results in more detail.

During the past year our theoretical work on the collective acceleration of electrons using the upper-hybrid (UH) mode has advanced significantly. We have developed an linear eigenmode code that enables us to explore a broad range of parameters to identify a promising set for initializing our two-dimensional time-dependent relativistic electron fluid code as well as finding an experimentally viable regime. The time-dependent code we have developed will be used to explore the nonlinear propagation characteristics and practical methods for growing the desired mode via applied wiggler fields.

From the eigenmode code, we have found upper-hybrid modes propagating at phase velocities equal to the speed of light which have a large axial electric field. In figure 25 are a set of dispersion curves for the guide parameters given in the caption which are intended to be easily achievable with the experimental apparatus available in the laboratory. The upper-hybrid mode crossing the light line is indicated by a circle. In figure 26 we show the corresponding eigenfunctions for E_θ and E_z . These modes are hybrid modes in that the E_θ and E_z are comparable in magnitude. Note that the sign of E_θ is such as to cause the electrons to $E \times B$ drift towards the axis where the accelerating field is largest. This self-focusing aspect of the UH mode is fortuitous.

The linear eigenmode displayed in figure 26 was initialized into the time-dependent code. In figure 27 are plots of E_z as a function of axial position near the axis for a sequence of times. The measured phase velocity in the time-dependent code is measured to be within 1% of c . The run in figure 27 is for small amplitude so that nonlinear effects are negligible. The mode was observed to propagate without distortion for electric field amplitudes up to about 2 MV/m for the particular parameters chosen. Considerably larger value of E_z can be achieved with higher current beams or maybe by going to higher electron beam energies. For example increasing the guide field to 1 Tesla and the beam density by a factor

Figure 25

Angular frequency (normalized to the cyclotron frequency) vs. wave number (normalized to the inverse guide radius) for a guide field of 0.2 T (cyclotron frequency of $3.518 \times 10^{10}/s$), guide radius of 1.5 cm, and plasma frequency of half the cyclotron frequency. This corresponds to a beam velocity of 0.89 c ($\gamma=2.2$), beam current of 2.94 kA, cutoff frequency 1.37 times the cyclotron frequency, injection voltage of 613 V, and electron number density of 9.7×10^{10} per cubic cm. The light line is included for reference, and labeled "c". One of the curves was not computed for all values to improve algorithm efficiency.

Figure 26
 Normalized electric field amplitude vs. radius (normalized to guide radius)
 for a wave number of 1.8 and angular frequency of 1.047 (normalized to
 inverse guide radius and cyclotron frequency respectively).

Figure 27
 z component of electric field (normalized to the guide magnetic field times the speed of light, 60.0 MV/m) vs. z (normalized to the guide radius, 1.5 cm). The curves are for various times determined by the adaptive time integration algorithm with the order corresponding to the labels. The times are from zero to 0.44 inverse plasma frequencies ($2.5e-11$ s). The phase velocity is approximately $3.08e8$ m/s, as measured from the figure. The calculated value, the angular frequency divided by the wave number, is $3.069e8$ m/s for this eigenmode.

of five increases the maximum linear axial field to about 50 MV/m at a phase velocity equal to c . We are currently concentrating on parameters that can be realized with our experimental equipment, later on we will explore the optimization of the axial electric field.

Presently, we are attempting to excite the UH mode by three-wave coupling through the application of an external magnetic TE wiggler. The wiggler period is chosen so that the UH mode on the light line couples to the wiggler field through a TE waveguide mode, see figure 26. The transverse electric field of the wiggler and the TE mode should couple through the substantial E_θ field of the UH mode. The potential advantage of using the TE-like wiggler and TE waveguide mode is that there should not be any significant E_z produced except that of the UH mode, thus detrapping of accelerated electrons by an incoherent E_z field is less likely to occur than if TM modes were used in the three-wave coupling process. The code modifications necessary to explore this excitation scenario have been made and we expect to have results shortly. Assuming that we are able to excite the UH mode by refining and tuning the guide parameters, our principal effort during the coming funding year will be to design an experiment which can be developed in the laboratory to demonstrate this new collective acceleration scheme.

[4] Current and Future Work

We plan during the rest of the current contract to focus our activities on a continuation of the existing programs. More specifically we plan to:

[i.] Continue the development of our coaxial amplifier arrangement including an investigation of the several options available for intermediate stage amplification, i.e. we shall not restrict our activities to klystron like configurations but will use a mix of cavities and amplifiers. The amplifiers to be used will fall in two categories: a.) Dielectric loaded amplifiers and b.) Two sided rippled wall amplifiers.

[ii] Extend our work on pencil beam microwave amplifiers in an attempt to eliminate the sideband structure. This will include work on alternate slow wave

structures including a dielectric loaded section in the tube with tapered input and output to minimize reflections. We shall also demonstrate rf acceleration in a short rf linac in order to show the applicability of pulse power driven, field emitter electron beam sources for the production of rf for accelerator applications.

[iii] Extend the work on Ferroelectric emitters to completely characterize these devices as electron sources. We shall work in two regimes, namely high current ~ 1 kA/cm² and at more modest charge levels of about 10^{11} electrons per pulse. In the latter case we shall measure the beam emittance and will attempt to generate very short duration pulses.

[iv] Continue our analytic and simulation work in support of the rf generation program.

[v] Continue the program of investigation of the upper hybrid mode with emphasis on the theoretical development of a workable design for parametric excitation of the wave, and conduct a parameter survey to find the range of acceleration electric fields accessible experimentally. We plan to restart our efforts at experimental excitation of the wave when the theoretical study has advanced to the point of showing the best method for wave excitation.

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