HIGH EFFICIENCY TWT AMPLIFIERS *

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Abstract

We report on a research program to increase the efficiency of relativistic traveling wave amplifiers to $> 50\%$. The two stage amplifier consists of a bunching periodic structure with phase velocity significantly higher than the beam velocity and a decelerating section with phase velocity significantly lower than the beam velocity. The position of the decelerating stage with respect to the bunching stage is chosen such that the narrowest bunches are sustained in the decelerating field for the longest possible time before significant debunching occurs. Two schemes are under investigation. In the first scheme, a resistive sever is placed between the two stages to suppress temporal phenomena. In the second scheme, the bunching and deceleration stages merge into each other by a gradual change in the iris radius over a wavelength. An absorbing section in this case is placed before the start of the bunching stage. Coaxial extraction geometry [1] is used in both schemes. Efficiencies obtained from MAGIC simulations are comparable to those obtained in high efficiency klystrons [2] (50-60%) but carry the important advantage of broad-bandwidth, low sensitivity on dimensions, low surface fields, and simplicity of design.

1 INTRODUCTION

The TWT is a potentially viable ultra-high power microwave source for various applications if the beam-to-electromagnetic energy conversion efficiency can be raised to over 50%. Specific advantages offered by the TWT, over other sources, include low surface electric fields, broad bandwidth, and low sensitivity to dimensions and beam quality. In this paper, we present a simple design of a high efficiency TWT based on a traveling wave bunching section merging into a traveling wave deceleration section.

The efficiency of a TWT is limited by inefficiencies in the bunching process, spatial and momentum spread of the bunches, and the entry of the bunches into the accelerating phase of the RF field. The usual technique suggested for increasing the efficiency involves tapering of the wave phase velocity so that the decelerated bunches remain within the decelerating phase of the wave.

The electric field in the amplifier arises from the quasi-static fields of bunches and the radiation field from decelerated electrons. The spatial position of bunches with respect to the wave can be changed by changing the local phase velocity in the slow-wave structure. This fact will be used in the design described here. However, the forces due to the collective effect of space charge strongly determine the spatial spreading of the bunch. Hence both the position and size of the bunch with respect to the radiation wave need to be considered for designing an efficient amplifier. Single particle or rigid bunch models which are often used the design of high efficiency devices, frequently neglect the effects of the quasi-static bunch forces on the electron dynamics. These fields are frequently comparable to the radiation fields in TWT's operating at a few 100 kV and few 100 A's, In order to design a high efficiency and high power TWT, it is necessary to use a fully non-linear and self-consistent analysis. This is best achieved by the use of PIC codes.

2 CONCEPTUAL ILLUSTRATION

In a traveling wave tube the electron beam bunches gradually accumulate in the decelerating phase as a result of interaction with the co-propagating structure wave. Uniform structure TWTs are usually operated such that the beam velocity is equal to or greater than the cold phase velocity in the supporting slow-wave structure. Typical efficiencies for synchronous structures are about 25%, which can be increased to 30-35% by use of a structure with a lower phase velocity. We propose to use a structure with phase velocity *faster* than that of the beam electrons to produce efficient bunching followed by a lower phase velocity region to extract bunch energy into RF field.

To illustrate the effect of different phase velocities on bunching and the self-consistent generation of rf power from bunch deceleration, we consider three PIC simulations performed with MAGIC code. For ease of presentation, we use a dielectric slow-wave structure. A uniform circular waveguide of radius 15.5 mm lined with a dielectric of radius 6 mm, and operated at 9 GHz. The system ends with a non-reflecting termination. A 700 kV, 500 A, 3 mm radius pencil beam is chosen for all simulations. In Fig.1 a,b and c, the axial electric field and the instantaneous beam current are shown, from simulations corresponding to cold wave phase velocities of $1.01c$, $0.90c$ and $0.82c$ respectively. (ϵ_r of the dielectric = 1.8, 2.1, and 2.4 respectively). Consider Fig.1a, corresponding to the 'fast wave' case. Even though the radiation wave grows at phase velocity $< c$, the the bunches lag the wave more than in the other two cases. This causes reduction in growth rate and a slow spatial rise in current. However, the peak current in the fast-wave case exceeds the peak current achieved in the synchronous and slow-wave cases. Because E_z for a given rf current is the least in this case, the bunch energy spread as well as its average energy drop (and hence rf power) is

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also the lowest for the fast-wave case. These conditions are desirable for a good buncher, but not for extraction of bunch energy into the electromagnetic field. As expected, the initial growth rate is highest for the synchronous case (Fig. 1b) and the saturation power is highest for the lowest phase velocity case (Fig. 1c). The latter result follows since the bunches are taken to lower velocities before they enter the accelerating phase of the wave.

We conclude that the amplifier in Fig. 1a is an efficient beam buncher and the amplifier in Fig. 1c is an efficient decelerator (hence rf converter). A combination of the two may be expected to result in a high efficiency amplifier. To make use of the bunching in Fig. 1a, a change in phase velocity in the slow-wave structure is needed close to the point where the bunches are beginning to enter the accelerating phase ($z \sim 42$ cm). At this point we use a 4 cm long transition to a region with $v_{ph} = 0.82c$. This transition and its corresponding effect on the amplifier dynamics is illustrated in Fig. 2. The narrow bunch from around $z \sim 40$ cm slips back into the center of the decelerating field within the transition region and rapidly loses energy to the electromagnetic field. This yields over 50% efficiency. Note that when the bunch has spread to a width that is comparable to a half-wavelength, then no real advantage is gained by further lowering the phase velocity since part of the bunch has inevitably entered the accelerating phase. Power should therefore be extracted close to the E-field maximum in Fig.2.

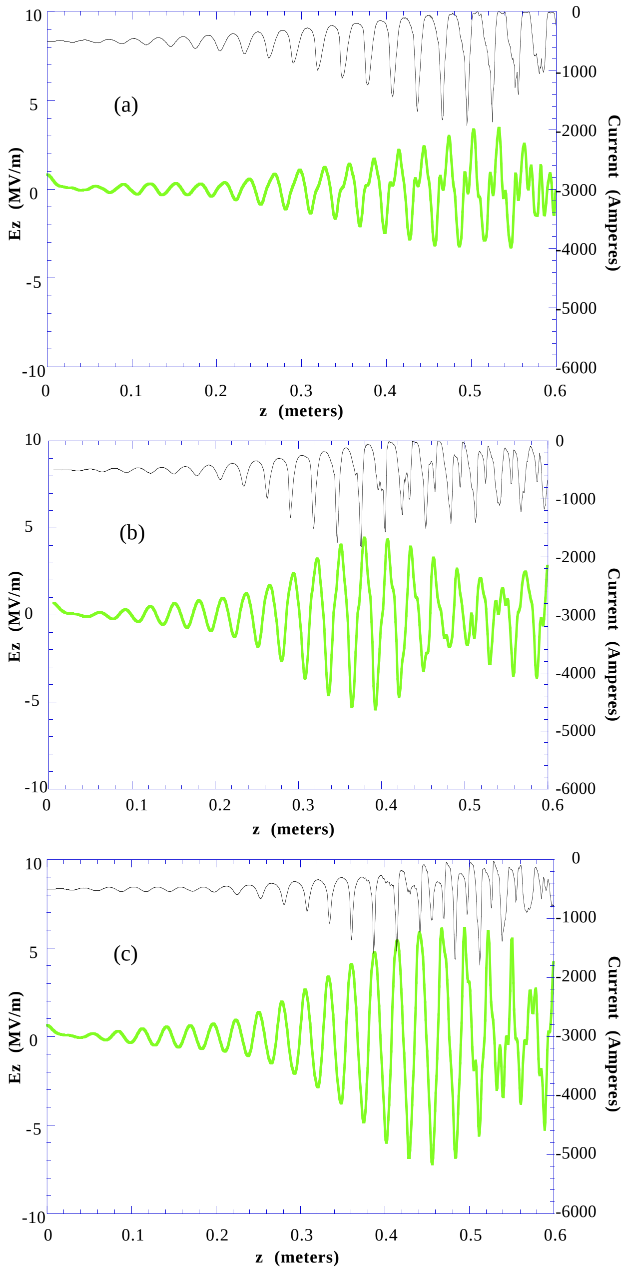

Figure 1: Current (top curve) and E_z (bottom curve) profiles for cases with cold phase velocities (a) $v_p = 1.01c$ (b) $v_p = 0.9c$, and (c) $v_p = 0.82c$, indicating highest bunching level and lowest E_z for the 'fast-wave' case.

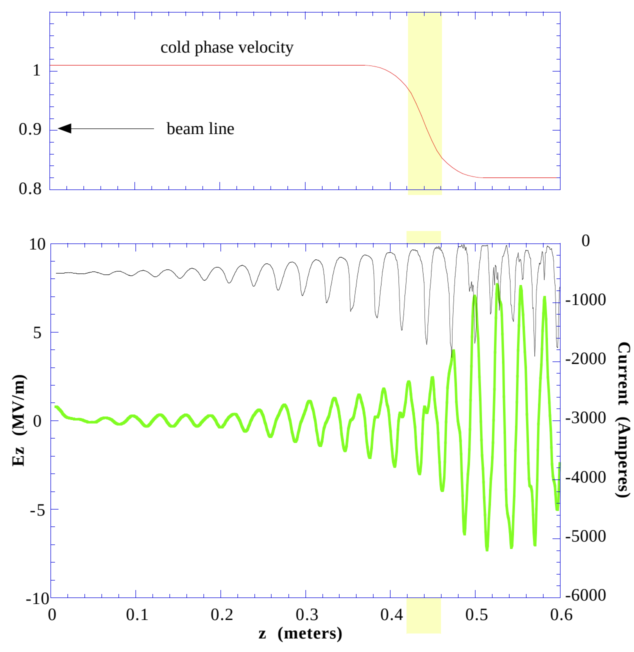

Figure 2: (c) Phase velocity = $0.90c$ for $z < 42cm$ and 0.82 for $z > 46cm$

3 EXPERIMENTAL IMPLEMENTATION I

The two-phase velocity concept is implemented with an iris-loaded waveguide periodic structure. The change in cold phase velocity from $1.2\ c$ to $0.75\ c$ is produced by changing the iris aperture while keeping the outer wall radius constant (Fig.3 top). The tapering at the ends is done to reduce reflections. An coaxial inner conductor placed in the output tapered section is used to shield the particles from the wave close to the power maximum, so that no re-acceleration occurs and hence the peak power is extracted. The coaxial extraction scheme, described previously [1], provides a broad-band, low-reflection coupling of peak rf power into a TEM coaxial mode. A SiC absorber is also placed at the input end of the amplifier to further absorb any residual reflections from the output of the system. At present, a short traveling wave section is used to provide a few percent initial modulation to the system. A MAGIC simulation with this structure demonstrates 200 MW power at 9 GHz into the coaxial guide, when a 700 kV, 500 A beam is launched into the system. This corresponds to 57% efficiency. The amplifier described has been fabricated and tests are presently in progress to check the validity of the design.

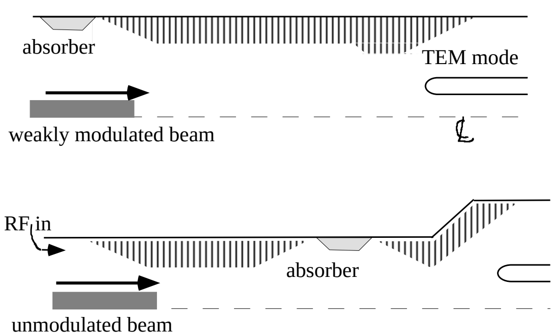

Figure 3: Experimental Implementation I (top) and II (bottom)

4 EXPERIMENTAL IMPLEMENTATION II

Fig.3 (bottom) shows a variation of the above idea. In this case, a SiC sever is placed between the TWT bunching and deceleration sections. The rf power obtained in the first stage is dumped into the absorber while the bunched beam traverses the sever and excites the required electromagnetic mode in the 2nd stage. The radiation field reconstructs from zero such that the bunches automatically lie in the decelerating phase of the electric field. This results in rapid growth of the rf field. The size of the first stage and the length of the sever are optimized via simulation to minimize the phase angle spread of the bunches entering the 2nd stage. The extraction section in this case is also enlarged to reduce the risk of rf breakdown. This also provides greater flexibility in the choice of radius and position of the inner conductor. Fig. 4 shows initial experimental measurements of the output power from the device. The

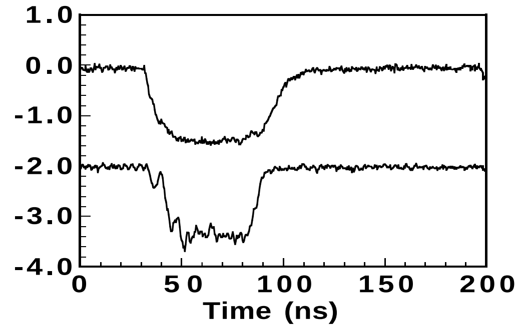

Figure 4: (Top) Beam current (Bottom) Output RF

upper part of the figure shows the beam current and the lower part the output rf envelope detected by an E_r probe, mounted in the side wall of the coaxial output section. The power level at the end of the first stage is a few MW with a single frequency output. The pulse is phase stable to $\pm 3.5^o$, which lies within error range of the diagnostic. At present the peak output power is found to be 45 MW for beam input of 800 kV at 300 A. Simulation done with 1000 kV, 500 A beams indicates an rf conversion efficiency of 50% with output power of 250 MW. Experiments are underway to change the modulator output voltage and current closer to the intended design.

5 CONCLUSION

We have proposed TWT configurations based on a two section slow-wave structure, such that the first section optimally bunches the beam, while the second section efficiently decelerates the bunches. The bunching and deceleration aspects of the problem are therefore treated on equal footing in order to maximize efficiency. MAGIC simulations indicate that 50-60% beam-to-electromagnetic efficiency can be achieved in both experimental designs described. Because of the pure traveling-wave nature of the interaction, the designs are not sensitive to input frequency or system dimensions. For example, a few centimeters change in the transition point of the structure only alters the efficiency by a few percent. Also a wide range of phase velocities can be chosen for the design of the two sections. The simplicity of the design, combined with all the desirable properties of the traveling wave interaction could could make this scheme a viable and efficient ultra high power microwave source in X-band. Design studies have also indicated that similar designs at 35 GHz are experimentally feasible and should yield efficiencies of $\geq 40\%$.

6 REFERENCES

[1] S. Naqvi, G. S. Kerslick, J. A. Nation, and L. Schächter, *Appl. Phys. Lett*, **69**, 1550 (1996).

[2] G. Caryotakis, *IEEE Trans. Plasma Sci.* , **22**, 683 (1994).