High-Efficiency TWT Design Using Traveling-Wave Bunch Compression

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Abstract—A bunch compression scheme designed to obtain high efficiency in relativistic traveling-wave tube (TWT) amplifiers is reported. Bunch compression is achieved by making the bunches stay in more positive slopes of the axial electric field in the amplifier. The resulting momentum gradient across the bunch tends to oppose space-charge spreading and helps to sustain short bunch lengths for long distances. A faster than light structure is employed to produce the required bunching. At the optimal bunching point, a transition is made to a lower phase velocity structure where the narrow bunches are decelerated. An RF conversion efficiency of $>50\%$ in an X-band amplifier is achieved in particle-in-cell (PIC) simulations. This contrasts strongly with the 20\%–30\% efficiencies achievable from typical relativistic TWT’s, where the bunching is not optimized.

Index Terms—Bunching, efficiency, phase velocity, relativistic electron beams, traveling-wave tubes.

I. INTRODUCTION

The operation of traveling-wave amplifiers for the generation of coherent electromagnetic radiation relies on the spatial bunching of an electron beam by an electromagnetic field and the simultaneous deceleration of the bunches by the same electromagnetic field. Whereas the net deceleration of bunches by the axial electric field is responsible for the growth of the electromagnetic power, the gradient of electric field across the bunch influences the velocity distribution of the particles, which, together with space-charge spreading in the bunch, determines the bunching profile in the system. At the saturation point of the amplifier, a significant portion of the bunch has entered the accelerating phase after losing a considerable fraction of its energy in the preceding decelerating phase. The usual techniques for raising the efficiency involve tapering of phase velocity, so that the bunches remain in the decelerating phase for a long time. However, phase adjustments alone are often not sufficient to obtain a high-efficiency amplifier. Due to space charge, the bunch will spread to a width that is about a half wavelength, and no phase adjustment will help keep the entire bunch in the decelerating phase thereafter. The efficiency of a typical uniform structure relativistic traveling-wave tube (TWT) lies between 20\%–30\% [1]. A careful tailoring of the momentum distribution of particles is needed to form and sustain short bunch lengths, in order to achieve higher efficiencies.

In klystrons [2], there is a clear separation of the bunching from the deceleration/extraction stage. Although no such distinctions are possible in a continuous-structure TWT, we can nevertheless designate a section as a “decelerating” section, in which the major portion of the bunch energy is lost. The section prior to that will be called the “bunching” section to facilitate description.

In this paper, the term “system” refers to the hot tube that is comprised of the beam in a slow-wave structure. The term “cold” is used to refer to the slow-wave structure in the absence of the beam. The properties of the system will first be related to the cold structure and the beam parameters. The analysis is extended to faster than synchronous structures (i.e., structures with a cold wave phase velocity greater than the beam velocity) that are required to produce efficient bunching. For relativistic amplifiers, these conditions entail the use of a structure with a cold wave phase velocity exceeding the speed of light. The trajectory of the bunch with respect to the wave phase is studied qualitatively and with the help of particle-in-cell (PIC) simulations. The role of the momentum gradient $\frac{\partial p_z}{\partial z}$ produced by the field gradient $\frac{\partial E_z}{\partial z}$ across the bunch will be carefully studied to determine the desirable bunching conditions in the TWT.

An amplifier comprised of a faster than synchronous bunching section merging into a slow decelerating section is proposed at the end of the paper. This design shows the feasibility of an X-band TWT amplifier with an efficiency greater than 50\%.

II. LINEAR ANALYSIS: RELATION BETWEEN HOT AND COLD TUBE PARAMETERS

From well-known Pierce theory [3], we know that the interaction between the beam and the slow-wave structure occurs when the synchronism condition

$$$(\omega - k_0 v_z) \sim 0 \quad (1)$$$

is satisfied.