THE MAXIMUM EFFICIENCY OF A CONVENTIONAL KLYSTRON OUTPUT CAVITY*

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Abstract

By using a photocathode instead of a thermionic cathode in a klystron, the possibility exists to make very short low energy spread bunches of high efficiency. However, there is a fundamental limit to the efficiency of a conventional output cavity, such as the one used in the SLAC XK-5 klystron. The fringing electric field in the drift tube acts on the beam as it leaves the output cavity and results in a net acceleration. All electrons which eventually reach the collector emerge from the drift tube with a substantial kinetic energy and as a result, the highest practical efficiency is about 80% for a 400 kV single output cavity tube. The behavior of these very short low energy spread bunches was calculated using MASK, a 2D field and particle program as well a much simpler 1D program. Using multiple output cavities, it may be possible to extract energy from the electrons more efficiently.

New methods of forming bunched beams of electrons such as using laser modulated photocathodes[1] or second harmonic bunchers[2] can improve the beam power to RF power conversion efficiency by shortening the bunch length and minimizing the energy spread of electrons within each bunch. With short low energy spread bunches, one can try to adjust the output cavity voltage and phase to bring all electrons in a bunch essentially to rest after having passed through the output cavity, implying an efficiency of 100%. However, if one examines the dynamics of electrons as they pass through the cavity and fringing fields in the drift tube, it becomes clear that it is not possible to arbitrarily slow down the electrons, they either emerge from the cavity with a substantial kinetic energy or they are reflected. The efficiency of an output cavity is therefore limited by the minimum kinetic energy electrons have when they emerge from the cavity/drift tube.

The dynamics of electrons passing through an output cavity were investigated using two different computer simulations. In both cases the output cavity resembles the one used in the SLAC XK-5 klystron which produces RF power at 2856 MHz. In one case, a short bunch of initially 2 picoseconds duration is simulated using the particle in cell simulation code called MASK. The charge in the bunch corresponds to a perveance of 0.05 micropervs, in the sense that a train of such bunches would have the same beam power as a continuous beam with that perveance, and the beam voltage is held at 400 kV. The cavity voltage and phase relative to the bunch starting time are varied to minimize the final kinetic energy of electrons which pass through the cavity.

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The MASK simulation was originally set up to predict the efficiency of the SLAC lasertron and to optimize the pulse length and beam power. For reference, the very short low energy spread bunch described above was tried and surprisingly gave no more than 81.4 ± 1% efficiency. This efficiency was obtained at a cavity voltage of about 450 kV and with the initial bunch voltage of 400 kV, giving a beam power of 2.5 MW. The bunch lengthened during transit from the cathode to the cavity to about 20 degrees of RF phase, and there was a spread in energy of electrons within the bunch of about ±3%. A normal bunch for the SLAC lasertron would have an energy spread of ±30%, lengthen to 100 picoseconds, and give an average beam power of 50 MW (see Fig. 1). The MASK calculation shows that the bunch is to some extent still intact after having passed through the cavity and that additional RF power could be extracted from it by a second cavity.

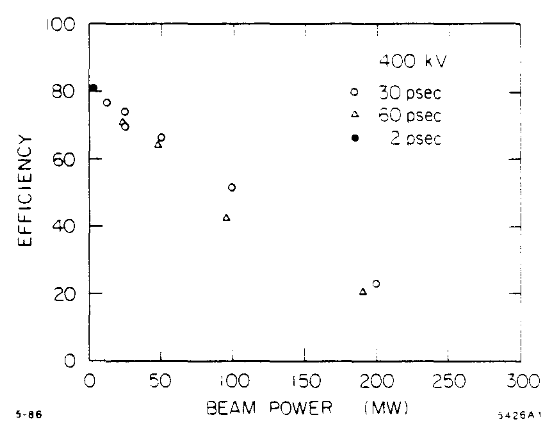

Fig. 1. MASK simulation results for the beam power to RF power conversion efficency for the SLAC lasertron using a single gap output cavity. At the design operating power of 50 MW the calculated efficiency is 66%. The highest efficiency 81.4 ± 1%, was obtained with a 2 picosecond low power bunch at a cavity voltage of 450 kV.

The second simulation replaces the multiparticle two dimensional code with a relativistic code to model a single electron under the influence of a one dimensional force of the form $f(z)\cos(\omega t)$ where $f(z)$ is shown in Fig. 2 and ω is the cavity angular frequency. An electron is started with 400 keV a distance $8/\gamma$ from the cavity center, where γ is the attenuation constant appropriate to the drift tube diameter. The cavity phase is advanced one degree each cycle relative to the starting time of the electron and the trajectory of the electron is computed. When the electron has moved more than $8/\gamma$ away from the cavity center the calculation stops and the final energy energy is recorded. The calculation is performed at several cavity voltages.

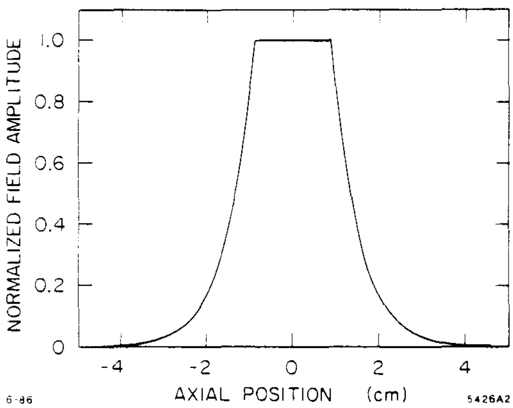

Fig. 2. The normalized amplitude of the longitudinal electric field used in the one dimensional model of electron dynamics.

Though the force used in the one dimensional simulation only crudely resembles the force in the MASK caluculation the calculated efficiencies are not very different. If the cavity voltage is set to 450 kV, the one dimensional model gives a maximum efficiency of 83.9%, compared with 81.4% calculated by MASK. However, the one dimensional model predicts that higher efficiencies are possible at very high gap voltages. For example, at a gap voltage of 900 kV it predicts a maximum efficiency of 94%, but only for a few degrees of RF phase. If the efficiency is averaged over 20 degrees of phase, as it is in the MASK calculation, the efficiency drops to about 58%. If it is not possible to produce a useful beam with bunching better than that in the 2 picosecond low power bunch used in the MASK calculation, then these calculated efficiencies represent an upper bound on the efficiency using the XK-5 output cavity.

It is not clear that there is a concise explanation for the fact that the conventional output cavity used here cannot slow electrons effectively to much less that 20 % of their initial energy because of the complicated nature of the dynamics. If fact, the dynamics of high efficiency electrons may become chaotic at phases near the optimum.[3] But the following consideration should make it seem plausible that it does indeed do so.

If an electron were brought to rest in presence of the oscillating electric field in the cavity or drift tube, unless it was very near the cavity center it would be accelerated away from the cavity center regardless of the RF phase or amplitude. If the phase is such that it initially accelerates the electron away from the cavity center then after one half an RF cycle the field will be of opposite direction but of less strength and the electron will acquire a net momentum away from the cavity. If, on the other hand, the phase is such that the field initially accelerates the electron toward the cavity, a half cycle later it will be stronger and in the reverse direction and again give a net momentum to the electron away from the cavity. This is only true if the electron does not get back to the cavity center during the course of motion.

In principle two conventional cavities used together, such as the double gap cavity used in the experimental 150 MW kylstron[4] could have a higher maximum efficiency than one. If the efficiency of the first cavity is 80%, 20% of the energy remains for the second cavity to extract. If the second cavity also has 80% efficiency, a total of 96% of the energy can be extracted. If the first and second cavity are tuned to extract the same power ($P_{RF}/2$) and the second cavity is 80% efficient, then the power of the spent beam P_F is

$$\frac{0.2(\frac{P_{RF}}{2})}{0.8} = P_{RF}/8$$

and the maximum efficiency is

$$\frac{P_{RF}}{P_{RF} + P_F} = 88.9\%$$

References

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