Increasing Klystron Efficiency Using COM and BAC Tuning and Application to the 5045 Klystron

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Abstract: The Core Oscillation Method (COM) and Bunch-Align-Compress (BAC) cavity tuning schemes are discussed and applied to the re-design of the 5045 klystron towards achieving the highest efficiency micro-perveance 2.0 tube ever built.

Keywords: klystron; BAC; COM; efficiency; second harmonic cavity;

Introduction

Klystrons have always been the primary RF source used to power accelerators. There are multiple reasons for this. They have high gain, low phase noise, but only moderately high efficiency, which can be estimated by the empirical relation $\eta_{max} = 78 - 16\ \mu K$, where K is the beam perveance ($I_o\ V^{-3/2}$). Achieving high efficiency (>70%) in a high power klystron requires either relativistic beam voltages or combination of many lower voltage beams which significantly increases complexity and cost. Efficiencies of commercial klystrons are typically 40-60%, a range that has essentially seen little change for several decades.

Somewhat surprisingly however, given the technology maturation one would expect for a device which was invented more than sixty years ago, a new design method for klystrons has been recently proposed [1]. The authors of this work refer to this new technique as the "BAC" method and show a path for obtaining significantly higher efficiencies than obtained in current klystrons. We have been studying this approach and found it truly does provide an avenue for achieving significant efficiency enhancements in a practical device. Using the BAC technique we have redesigned our 65 MW S-band klystron (model 5045) and, even though we constrained the design to leave the tube "plug-compatible", computer simulations show a 23% increase over the present efficiency. The current 45% efficiency of the 5045 falls quite close to the empirical prediction for the 2 μK of this tube so the predicted efficiency for our BAC design represents a significant improvement over the state of the art in klystron design.

BAC and COM Tuning for High Efficiency

The primary limitation to achieving high efficiency in klystrons is the action of the space charge forces in the electron beam. These forces limit the ability to introduce a strong density modulation longitudinally along the beam direction. Particles that fall in the desired part of the RF cycle are referred to as being in the "bunch" and are decelerated by the RF fields in the output cavity and contribute to the output power. Those outside the bunch (sometimes referred to as the antibunch) are accelerated by the output cavity fields and reduce the interaction efficiency (Figure 1).

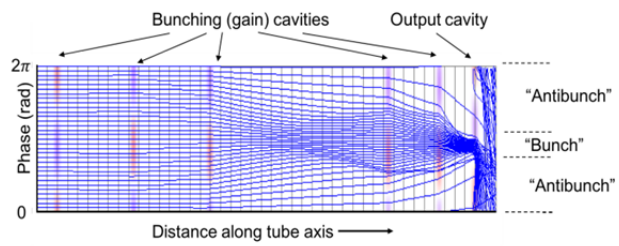

Figure 1. Typical phase space plot of particles in klystron interaction simulation.

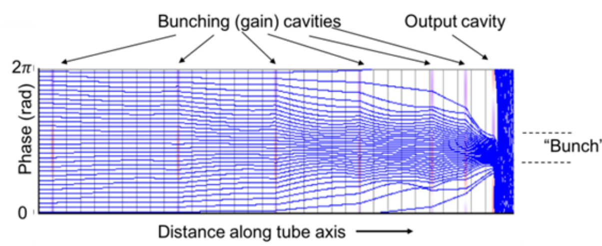

Figure 2. Phase space plot of particles for COM design klystron. Note the lack of particles outside of core group.

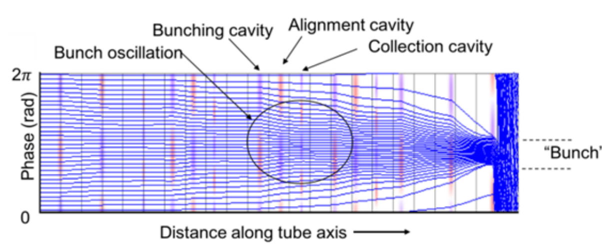

Figure 3. Phase space plot of particles for BAC design klystron.

An alternative design approach for achieving very high efficiency klystrons was proposed in 1999 by Bajkov [2] which is typically referred to as the "core oscillation

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method" (COM). Instead of using strong bunching forces with a series of closely spaced gain cavities as done in a traditional design (which results in a significant fraction of particles outside the bunch) the idea is to significantly increase the spacing between cavities. This new spacing is set to the bunch oscillation length which is the distance at which the bunch compacts in phase space and then starts spreading again due to the increased space charge forces. This process is shown in Figure 2. Using this cavity spacing allows the antibunch particles to monotonically approach the central bunch. Simulations of klystron interaction designed using this approach can have efficiencies approaching 90%. However, this design method has a significant disadvantage in that the required lengths are considerably longer, with a typical length increase of 50 to 100% more than a conventionally designed klystron.

The recent work of Guzilov [1] provides a method to achieve the efficiency enhancement of a COM design klystron but in a considerably reduced length. This is achieved by introducing triplets of cavities to "bunch, align and collect" (BAC) the electrons in such a way that the effective bunch oscillation length is greatly reduced. Using the BAC technique, design efficiencies approaching those obtained in COM designs can be achieved but in a length that is only marginally longer (10-20%) than conventionally designed klystrons.

These cavity triplets reduce the effective bunch oscillation length as follows. The first cavity provides the traditional bunching mechanism used in a conventional design which is to accelerate particles downstream of the bunch center while decelerating those ahead of the bunch center. The second "alignment" cavity modifies the particle velocities so they are no longer converging to the bunch center. This velocity modulation effectively forces the point at which the bunch oscillation width starts expanding so that it occurs in a much shorter distance than would have otherwise. The third cavity (tuned for the second harmonic) primarily effects the particles in the antibunch and modifies their velocities so they approach the bunch center while those particles in the bunch core are diverging away, with the result that more of the antibunch particles are brought into the main bunch.

Applying BAC Tuning to the 5045 Klystron

The 5045 klystron was introduced in the 1980's as the RF source for accelerating particles in the SLAC linac. After initial modifications to minimize infant mortalities the tube proved to be a very robust RF source with a cumulative MTBF of more than 50,000 high voltage hours [3].

The 5045 klystron design has remained largely unchanged over the last couple decades. Although the design is robust, the BAC principles discussed above have been applied to achieve an even more efficient design.

The new design improves the klystron efficiency from 45% to 55% by adding 4 cavities to the drift section (Figure 4) and applying the BAC method [1]. Improving the efficiency beyond 55% is easily achieved but restricted due to re-use of the existing gun (resulting in poor cavity coupling) and fixing the circuit at its original length. These design tradeoffs were made to reduce fabrication cost and to maintain compatibility with the existing SLAC linac.

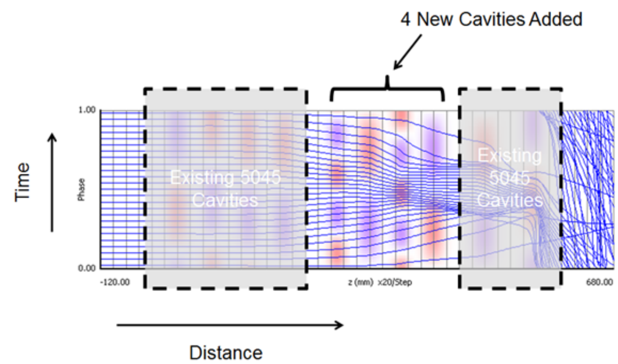

Figure 4. Phase trajectories for a high efficiency 5045.

Summary

BAC and COM tuning schemes are presented as an approach for improving klystron efficiency beyond the state of the art. The BAC method is applied to the 5045 re-design. The new tube will be hot tested mid-2016.

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