

# MAGIC2-D Simulations of High Efficiency Klystrons using the Core Oscillation Method

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**Abstract** — Klystrons employing traditional monotonic electron bunching are capable of efficiencies up to  $\sim 70\%$ . The use of the core oscillation method (COM) of electron bunching has predicted a significant improvement in efficiency towards  $90\%$ . Here, we document refinements on previously presented geometries, with PIC simulations predicting efficiencies up to  $85\%$ .

**Keywords**—*klystron; high efficiency; core oscillation method; MAGIC2-D.*

## I. INTRODUCTION

Several large-scale particle accelerators projects, such as the Compact Linear Collider (CLIC) [1] and the Future Circular Collider (FCC) [2] are currently in the design stage. Their RF requirements are expected to be on the order of  $100$  MW. Due to the significant increase in RF power demand when compared to the currently operating Large Hadron Collider (LHC) [3], the efficiency of the RF sources should be maximized, to reduce the overall operational and installation costs.

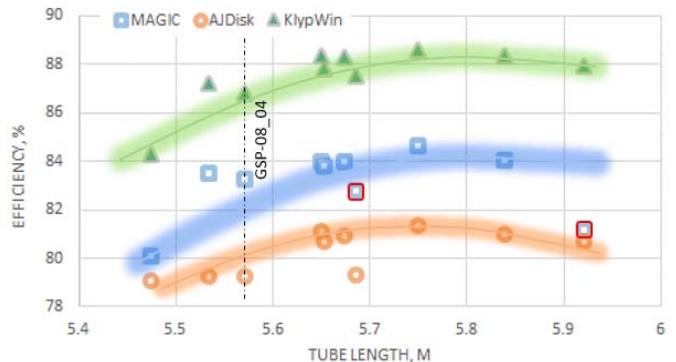
Klystrons are the most common multi-MW RF power sources which are used to drive particle accelerators. The existing commercialized klystron technology offers efficiencies up to  $70\%$  in such devices. Recent studies in novel klystron bunching mechanisms [4], including the core oscillation (COM) [5,6] and BAC [6-8] methods have predicted increases in efficiencies to greater than  $80\%$ .

PIC simulations of an  $82\%$  efficient single beam COM klystron has been reported [9]. In this paper, we present subsequent refinements which result in an increase in predicted efficiency up to  $85\%$ .

## II. NUMERICAL SIMULATION

The original GSP-08\_04 klystron is an 8 cavity,  $800$  MHz,  $1.4$  MW tube with an electron beam voltage of  $133.85$  kV, beam current of  $12.551$  A, and simulated efficiency of  $82\%$  [9]. This klystron design was used as a starting point for refined post-optimization in an attempt to obtain improved performance. This optimization was done using the 1D klystron code KlypWin [5] which allows for global optimization with many (up to  $50$ ) free parameters. Through optimization, the drift tube and electron

beam radii, beam voltage and current, cavities gaps and impedances were kept constant, whilst all the other parameters were set free within a few percent window. In the process over  $20,000$  cases were simulated, of which  $10$  tubes were selected for further analysis using the 1D code AJDISK [10] and the 2D PIC code MAGIC [11]. The performances of these tubes simulated by the various codes are summarized in Figure 1. All tubes showed good performance in the wide range of parameters, with similar trends over the different codes being used. For further illustration, we have selected the tube which showed best performance with  $84.64\%$  efficiency obtained in 2D PIC simulations (referred as 08\_04\_08).

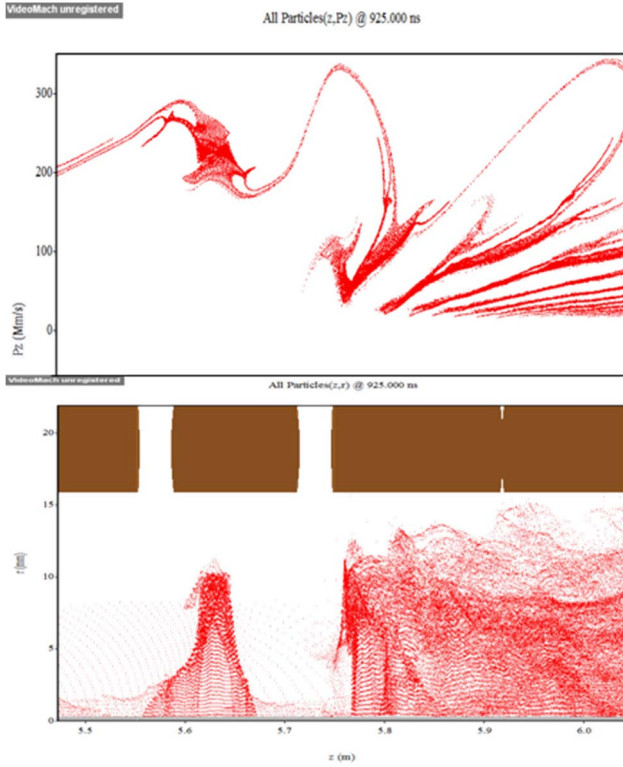


**Figure 1 – Predicted efficiencies of 10 selected klystrons simulated by different computer codes.**

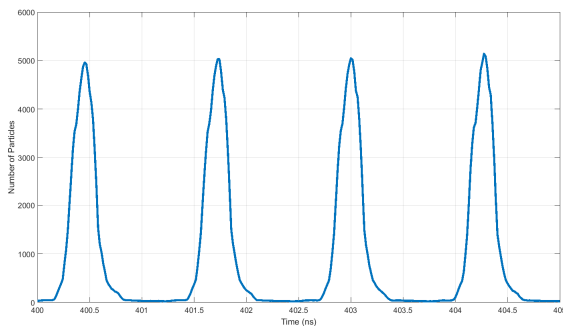
On simulating this tube in MAGIC2-D, a maximum output power of  $1.42$  MW in saturation was achieved for an input power of  $6$  W, corresponding to power gain of  $53.7$  dB. For all input power levels considered, the output power is stable, with no reflected electrons predicted. The instantaneous bunch profiles in  $P_z$ - $Z$  and  $R$ - $Z$  phase-spaces at the final two cavities are shown in Figure 2. These simulations confirm that COM is a reliable method to provide strong bunch saturation. The number of electrons contained in the anti-bunch (Figure 3) is less than  $1\%$  compared with the bunch.

The radial bunch stratification, i.e. radial variation of the bunch length at the output cavity entrance is the common issue

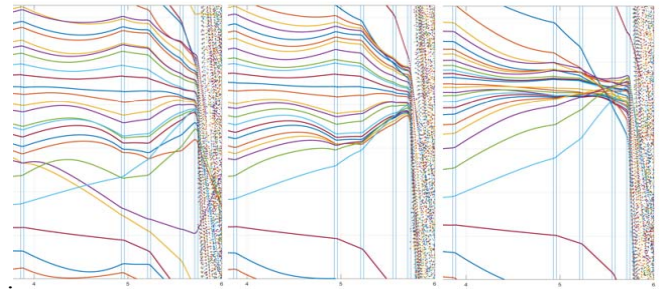
in klystrons that limits their performance. This effect is due to the radial mismatch between space charge forces and kinetic momentum received by electrons from bunching cavities. As a result, the longitudinal modulation depth is proportional to the radial offset within the bunch. Ultimately, the particles located close to the bunch radial edge will receive excessive deceleration in the output cavity and will be reflected. This effect was partially mitigated in the 08\_04 and 08\_04\_08 klystron designs by tuning of the last three bunching cavities. These cavities mostly affect the electrons at the bunch longitudinal periphery with least effect on the bunch core. However, the bunch still has visible radial stratification. This can be illustrated further in Figure 4, where Applegate diagrams calculated at different radial offsets are shown.



**Figure 2 –  $P_z$ - $Z$  (top) and  $RZ$  (bottom) phase-space profiles of the electron beam at the final two cavities.**



**Figure 3 – Bunch time profiles integrated locally at the entrance of the output cavity.**



**Figure 2 – Applegate diagrams for on-axis particles (left),  $x0.5 R$  beam (center) and close to  $R$  beam (right) in MAGIC2-D.**

### III. SUMMARY

Post optimizations of the GSP 08\_04 klystron have been performed. In the new design, the efficiency is increased from original 82.7% up to 84.64%. This enhancement of 2% is incredibly important when considering the impact on the RF demands of future particle accelerators.

### ACKNOWLEDGMENTS

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