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HIGH EFFICIENCY KLYSTRONS USING THE COM BUNCHING TECHNIQUE

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Numerical simulations of 800 MHz klystrons employing the core oscillation method (COM) of electron bunching have predicted efficiencies approaching 85%. This represents a significant improvement over the ~70% offered by commercially available multiple-beam klystrons (MBK's). Here, we present recent simulations describing refinements of COM klystrons.

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Numerical simulations of 800 MHz klystrons employing the core oscillation method (COM) of electron bunching have predicted efficiencies approaching 85%. This represents a significant improvement over the ~70% offered by commercially available multiple-beam klystrons (MBK's). Here, we present recent simulations describing refinements of COM klystrons.

INTRODUCTION

Upcoming large scale particle accelerators, such as the Future Circular Collider (FCC-ee) [1], the Compact Linear Collider (CLIC) [2,3], the International Linear Collider (ILC) [4], and European Spallation Source (ESS) [5] will have RF power demands extending towards hundreds of MW. At present, the maximum efficiency of a suitable RF source (klystron or IOT) is on the order of 70%; therefore, a significant amount of energy is effectively wasted as heat [6]. Improving the efficiency of the RF source is therefore of critical importance to reducing the overall costs and improving the carbon footprint of the installation.

Klystrons are an attractive RF source, owing to their stability, operating frequencies, output powers, and efficiencies of approximately 65%. The limiting factor lies with the profile of the electron bunch, as it approaches the output cavity of klystron, as well as the velocity of the slowest electron leaving the output gap. To maximise the efficiency of the tube, the spatial and phase profile of the bunch should be such, that, after it is decelerated by the output gap, each electron has identical velocity – a so-called monochromatic bunch. To that end, efforts have focussed on novel electron bunching mechanisms [7].

The core oscillation method (COM) is a promising bunching scheme, which efficiencies of up to 90% have been demonstrated in 1-D simulation [8,9]. In this paper, we present recent results from numerical simulations of klystrons employing the COM technique.

COM BUNCHING MECHANISM

In traditional klystrons, electrons are monotonically moved towards the centre of a single bunch, as the progress along the length of the tube. At the output gap, the electron bunch does not contain all available electrons within it, with some being contained in a so called 'anti-bunch'. Therefore, these electrons do not contribute any energy to the output RF signal, and will instead be accelerated by the AC signal in the output gap. As a result, the overall efficiency of the device is limited by the number of un-bunched electrons contained in the anti-bunch.

The core oscillation method (COM) [8,9] is based on the non-monotonic bunching technique, where, along the length of the klystron, electrons at the periphery of the bunch gradually approach the bunch centre. Simultaneously, the core of the bunch experiences an oscillation in its phase, due to its space charge causing it to expand, and the momentum delivered by successive bunching cavities causing it to contract. The cavity RF fields have a weak effect on the periphery electrons (phase of $\pm\pi$ with respect to the core); as a result, COM klystrons require a substantial increase in their interaction length to capture all electrons in the bunch (a full saturated bunch). However, very high efficiency klystrons can result. To form the FSB, the electrons must not overtake each other in the output gap [8].

This COM technique can be seen in Figure 1b, which shows electron trajectories in phase space, modelled in AJDISK [10]. Here, the de-bunching of the core can be observed between successive cavities (shown by vertical lines in Figure 1), as a contraction and expansion of the centre of the beam, while most of the peripheral electrons are seen to move into the bunch centre before the output. For comparison, Figure 1a shows the traditional bunching employed in the SLAC 5045 klystron, where a significant number of electrons are not contained within the output bunch. This tube has an efficiency of ~45%.

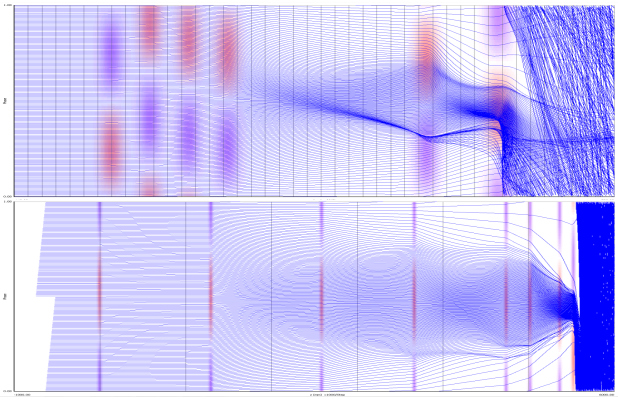

Figure 1: Electron phase profile of a) the SLAC 5045 klystron, and b) a klystron employing the Core Oscillation Method (COM).

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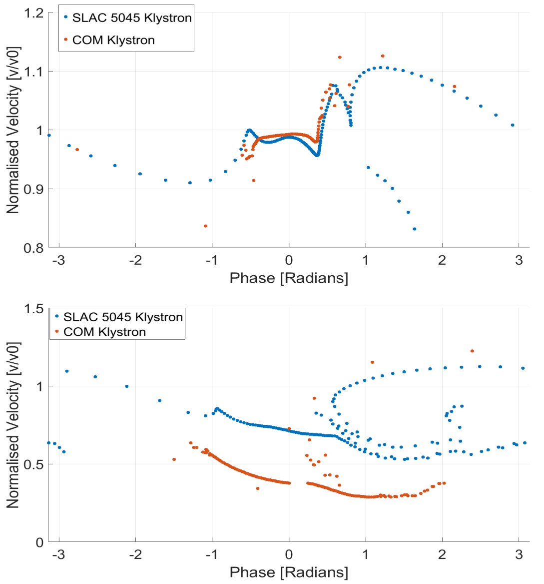

Figure 2: Comparison of arrival functions a) entering, and b) exiting the output cavity of the SLAC 5045 and a COM klystron.

NUMERICAL SIMULATIONS

Numerical simulations of eight cavity, 800 MHz klystrons employing COM have been performed [11]. These designs primarily examined electron beams with relativistic perveances of 0.213 µK, with the length of the devices being ~ 6 m. Good agreement was observed across a variety of 1-D, 2-D and PIC codes, predicting a stable klystron with efficiencies greater than 80%.

A subsequent optimisation, where more than 20,000 klystrons were investigated, yielded several configurations which were investigated further [12]. In this process, the electron beam, cavity impedances and klystron frequency were kept constant, while the individual cavity frequencies, external Q factors and cavity spacing were set as free parameters. The configuration (08_04_08) which produced the highest efficiency following this process, yielded a predicted maximum efficiency of ~84.6% in MAGIC2-D. The length of the klystron remains ~6 m. The power and spectra of the output signal are shown in Figure 3, with the stability of the tube apparent, although there is a small ripple on the signal.

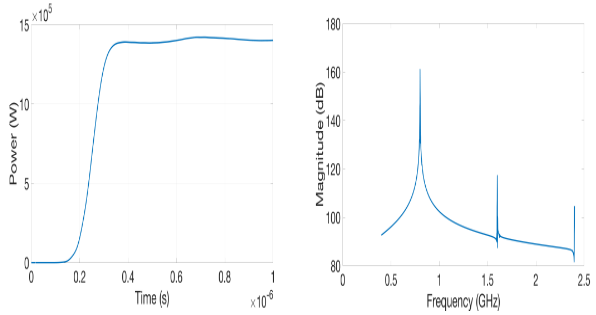

Figure 3: Predicted output power and spectra for the 08_04_08 klystron, from MAGIC2-D.

To gain additional insight, consideration is given to the electron bunch around the output gap. Figure 3 shows the electron bunch in R-Z space around the final three cavities for the optimised klystron, and also for a configuration which predicted reflected electrons, with a maximum efficiency of 79%, from MAGIC2-D. Prior to the output gap, both bunches have a triangular shape. However, a pedestal effect is observed on-axis for the optimised case, while the unstable klystron has a trailing tail. This effect is known as radial bunch stratification [7], and results from the radial mismatch between the space charge forces of the beam and the cavity impedance. The corresponding electron momentum for the optimised case evolving along the length of tube is shown in Figure 5.

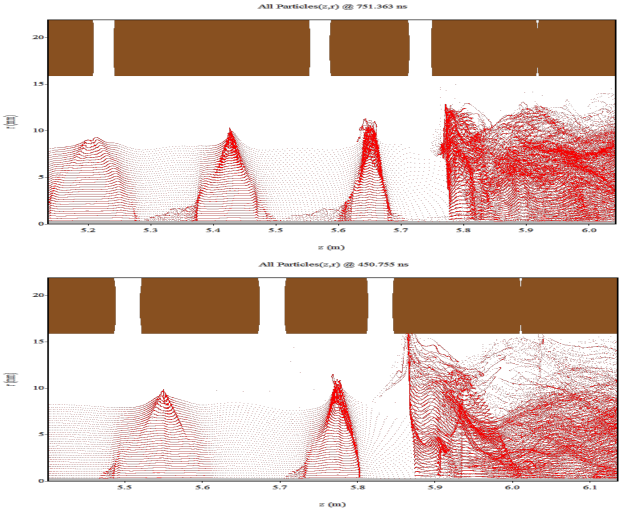

Figure 4: Electron bunch profile in a) the optimised case, and b) unstable klystron, simulated by MAGIC2-D.

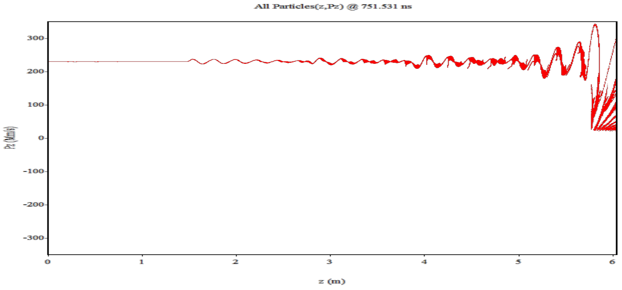

Figure 5: Electron momentum along the length of the optimised klystron, simulated by MAGIC2-D.

To quantify the degree of radial stratification, Applegate diagrams are constructed in MAGIC2-D. Several test particles are emitted over 1 RF period after the klystron has reached saturation, with their position and velocities tracked through the geometry. From this data, the particles phase with respect to the RF is constructed. Figure 6 shows the resulting Applegate diagrams for the optimised case, for electrons on-axis and at 60% of the beam radius. Here, each trace corresponds to an individual particle. The core oscillation behaviour is visible, with the core contracting and expanding between cavities, and peripheral electrons moving into the core at the output. The phase width of the bunch varying across the radius of the beam.

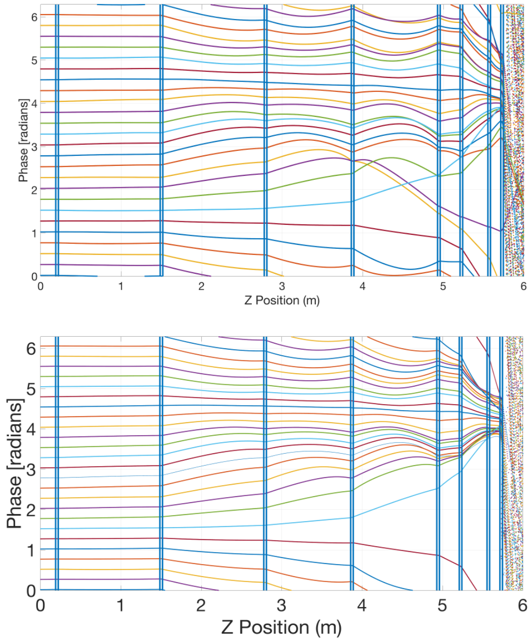

Figure 6: Applegate diagrams for a) on-axis, and b) at a radius of 5.2 mm, for the optimised klystron, simulated by MAGIC2-D.

This can be examined further by examination of the electron velocity arriving and exiting the output cavity, seen in Figure 7. Comparing to

Figure 1, the arrival function distribution is similar towards the middle of the beam, with the head of the bunch travelling slower than the tail. On-axis, however, the distribution is almost flat. For both radii, there is a significant velocity spread of particles exiting the output cavity, indicating a departure from the ideal case.

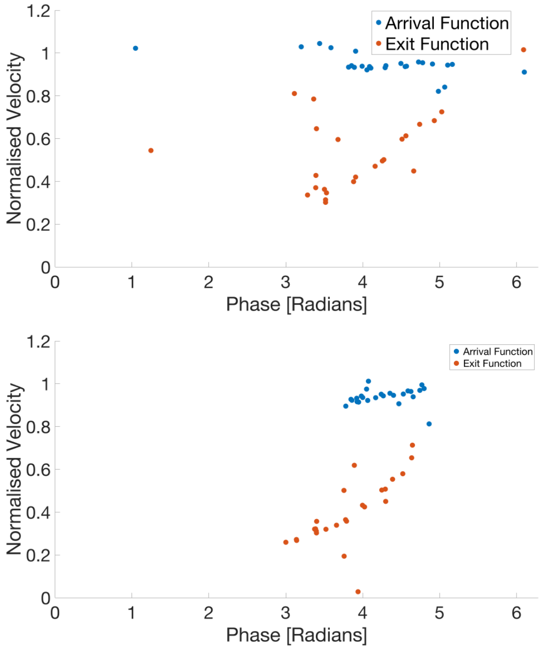

Figure 7: Arrival and exit velocities of electrons, at a beam radius of a) on-axis, and b) 5.2 mm, simulated by MAGIC2-D.

SUMMARY

Optimisation of a COM klystron has predicted an increase in efficiency of to 84.64%. Analysis of the electron bunch at the output gap illustrates the importance of spatial and phase profile of the bunch, in order to maximise the efficiency of the tube. Given the significant length of the klystron, efforts are now focussing on scaling these designs - retaining the high efficiency of the COM technique, in a shorter tube.

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