# HIGH EFFICIENCY KLYSTRON DEVELOPMENT FOR PARTICLE ACCELERATORS

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*Abstract*

Presently, state-of-the-art klystrons operate at efficiencies of up to 65%. Through the use of novel bunching mechanisms, it is possible to improve the efficiency towards 90%, which will be beneficial for reducing the power consumption of future particle accelerators. An overview of these bunching schemes, supported by results from numerical simulation and experiment are presented.

## 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] are expected to require RF powers in the 10-100 MW range. For comparison, the currently operational, Large Hadron Collider (LHC) [6], has a total RF drive of 5 MW. Due to the significant increase in RF power, it is advantageous to maximise the efficiency of the RF source, in order to reduce their running costs.

Klystrons are an attractive RF source for such applications, owing to their stability, operating frequencies, output powers, and efficiencies. In terms of efficiency, current state of the art klystrons can deliver a maximum 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. In order 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.

The High Efficiency International Klystron Activity (HEIKA) collaboration seeks to make improvements to the overall efficiency of klystrons by considering these issues. To that end, a number of novel electron bunching mechanisms have been proposed. In this paper, a brief discussion, along with numerical and experimental results of these novel schemes in operation, will be presented.

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## BUNCHING MECHANISMS

In traditional klystrons, electrons are monotonically brought towards the centre of a single bunch along the length of the device. At the output gap, the final bunch does not contain all available electrons within it, with some being contained in a so called 'anti-bunch'. Therefore, these electrons do not provide any energy to the output RF signal. As a result, the overall efficiency of the device is limited by the number of un-bunched electrons contained in the anti-bunch. The novel bunching mechanisms investigated by HEIKA will be discussed.

### *Core Oscillation Method (COM)*

The core oscillation method (COM) [7,8] 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); therefore, COM klystrons require a substantial increase in their interaction length to capture all electrons in the bunch. However, very high efficiencies (> 90%) have been observed in 1-D simulations.

This process can be seen in Figure 1, which shows electron trajectories in phase space, modelled in AJDISK [9]. 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 the outlier electrons move into the bunch.

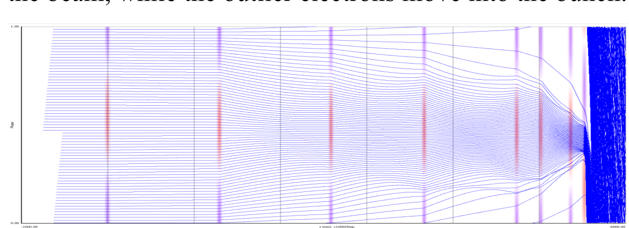

Figure 1: Electron phase profile of an 800 MHz klystron employing the Core Oscillation Method (COM).

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Numerical simulations of eight cavity, 800 MHz klystrons employing COM have been performed [10]. These designs primarily examined electron beams with relative perveances of 0.213 μK, with the length of the devices being approximately 6 m. Good agreement was observed across MAGIC2-D, TESLA, KLYS2-D and KlypWin, predicting a stable klystron with efficiencies greater than 80%. Subsequent optimisation finally established a design with a power production efficiency of 84.64%, with the output power from MAGIC2-D shown in Figure 2.

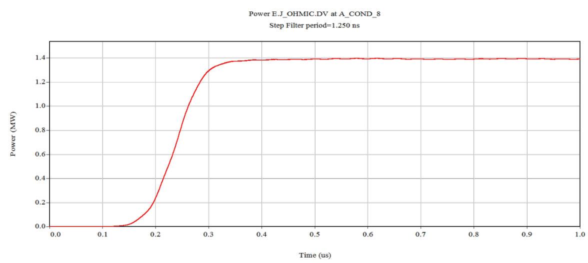


Figure 2: Output power of an 800 MHz klystron employing COM, with efficiency of 84.64%.

On examining the electron bunch profile prior to the output cavity, it can be seen that the bunch is triangular in shape (Figure 3a), with a pedestal close to the axis. This effect (radial bunch stratification) is due to the radial mismatch between the space charge forces and RF impedance of the klystron. This effect can be mitigated by employing a hollow beam [11]. In this case, the absence of electrons on axis allows the formation of a slab-like bunch prior to the output gap (Figure 3b). Numerical simulations of this configuration predict stable operation, with efficiencies of greater than 86%.

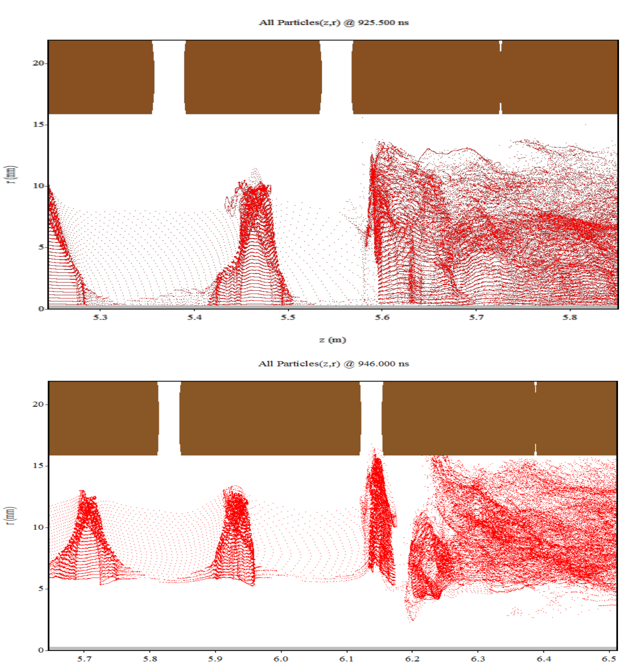


Figure 3: Electron bunch profile in a) cylindrical beam, and b) hollow beam, simulated by MAGIC2-D.

The X-band 50 MW, 12 GHz XL-5 klystron has previously been reported to have an efficiency of 40% [12]. Early AJDISK simulations of a modified XL-5 design employing COM, predict output power of 40 MW, with efficiencies in excess of 70%. This design, although increasing in length over the original (~35 cm) is only on the order of 50 cm in length.

### *Bunching-Alignment-Collection (BAC) Method*

The BAC method [13] is a technical extension of the COM method, allowing a reduction in the klystron length by a factor of two, while preserving the high efficiency. In this scheme, a set of three cavities is used to “bunch, align, and collect” (BAC) the electron bunch. Here, the first cavity serves as a “traditional” bunching cavity; the second aligns the electron velocities, while the third cavity (set at the 2$^{nd}$ harmonic) primarily effects the particles in the anti-bunch, causing them to be directed more rapidly towards the core of the bunch.

AJDISK was used to re-design the existing SLAC 5045 S-band, 65 MW pulsed klystron, with the introduction of a BAC section [14]. The existing tube has an efficiency of 45%. With the addition of two BAC sections, the predicted efficiency (in simulations) is expected to be as high as 65%.

BAC has also been implemented in a prototype of an S-band multi-beam klystron (MBK) developed at VDBT (Russia). This is a retrofitted design of an existing tube, which has efficiency of 42%. By adding BAC sections, the simulated efficiency was above 65%, while maintaining the length of the klystron. The klystron has been constructed and tested at CERN [15], demonstrating an efficiency of 60%, as shown in Figure 4.

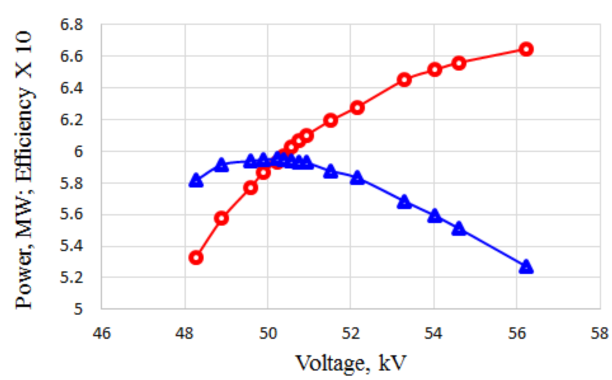


Figure 4: Efficiency (triangles) and RF power (circles) of the VDBT klystron at 2.99855 GHz, in saturation.

### *Third Harmonic Cavities (F-type Tubes)*

On introducing a third harmonic cavity, the advantages of COM and BAC can be extended further. The presence of the third harmonic creates three “virtual” cores within the electron bunch, which due to the space charge forces created, allows the electrons in the anti-bunch to move into the central bunch. This behaviour is shown in the phase diagrams in Figure 5, where the third and fourth



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cavities (vertical lines), are 2nd and 3rd harmonics, respectively.

An initial numerical study of a 1 GHz, six cavity F-Tube in AJDISK [16], predicted efficiencies of up to 88%. A subsequent re-design of the F-Tube to 800 MHz in AJDISK has predicted an efficiency of 80.25%. The inclusion of two additional fundamental harmonic cavities (FG-Tube), results in a smoother phase profile for the final bunch, with an improvement in efficiency to 80.87%. MAGIC2-D simulations of both designs are currently in progress.

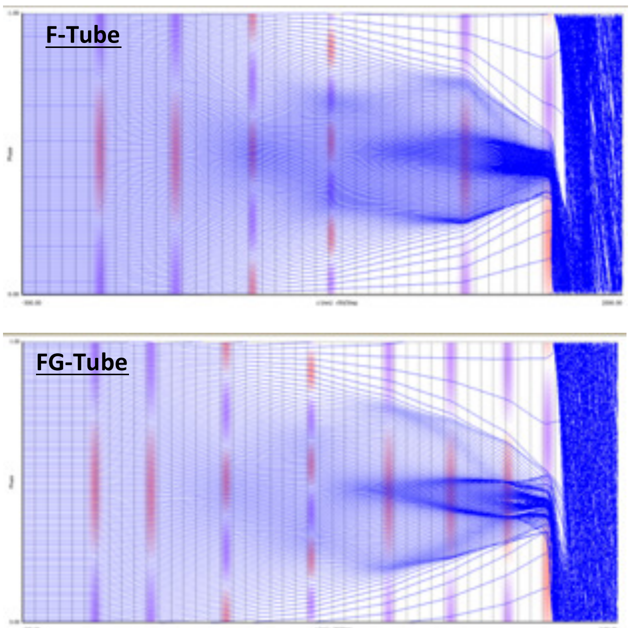


Figure 5: Electron phase profiles of the F-Tube and FG-Tube, from AJDISK.

## CONCLUSIONS

Through numerical investigations, the core oscillation method (COM), bunching-alignment-collection (BAC) and use of third harmonic cavities have been shown to improve on the efficiency offered by current state of the art klystrons. Early experimental testing of klystrons employing COM and BAC have demonstrated the strength of these bunching schemes, offering increases in efficiency when implemented in existing devices.

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