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# Pulsed Depressed Collector for High-Efficiency RF Systems

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**Abstract:** *Many emerging applications for high power RF sources place a premium on electrical efficiency. For pulsed systems, much of the energy is lost in the rising and falling edges of the beam current. This paper presents the concept of a pulsed depressed collector and the resulting improvements in system efficiency.*

**Keywords:** Collectors; RF Sources; Efficiency; Modulators; Power Supplies

## Introduction

Depressed collectors have been successfully implemented for decades in electron devices [1-3]. Benefits include improved efficiency, reduced heat loading, and lower parasitic radiation emission. Partly due to difficulties with implementing the recovery power supplies for the collector for pulsed systems, utilization is most widespread with CW systems.

However, there are a large number of applications using pulsed RF sources which also place a premium on electrical efficiency. In addition, during the rising and falling edge of the beam current pulse, the energy is wasted because most applications require a stable RF phase, and therefore flat modulator pulse during the time when the RF drive is on. This places a constraint upon the modulator to produce very fast rising and falling edges. For example for a typical klystron tube with a rise time and fall time of 1µs and a flattop of 1µs, >35% of the energy into the klystron is wasted during the tails of the modulator pulse.

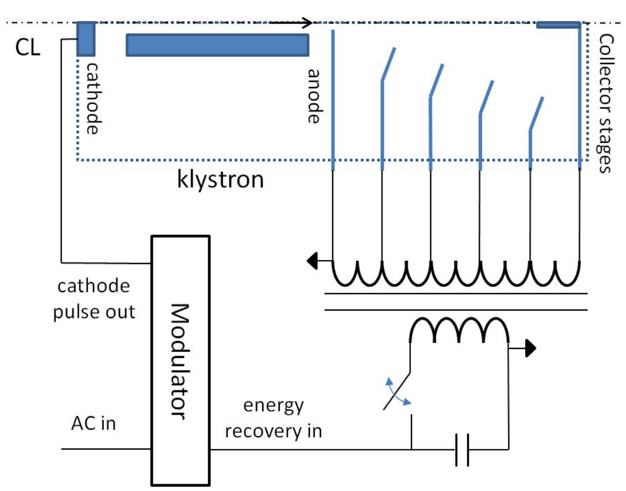


**Figure 1.** Block diagram of a pulsed depressed collector.

A pulsed depressed collector is proposed which uses a novel feed-forward energy recovery scheme. Using this, pulsed systems can achieve greater efficiency with minimal added complexity in the modulator circuit.

## Description

The proposed scheme works by recovering the energy for a given pulse, restoring the energy to the modulator, and discharging the energy in the following pulse. An example implementation is shown in Figure 1. The stages of the collector are electrically connected to separate taps on the primary of a step-down transformer. A storage capacitor is placed across the low-voltage secondary.

During the start of the pulse, the beam energy rises into the collector. As electrons are collected in the stages, the stage voltages rise. These time-varying potentials are determined by the characteristics of the transformer and the storage capacity. In effect, the stages are self-biasing; there is no need for a separate power supply. An example of a klystron beam profile along with ideal and simulated stage potentials is shown in Figure 2.

There are several advantages to this approach. First, it incorporates a mechanism to recover energy during the

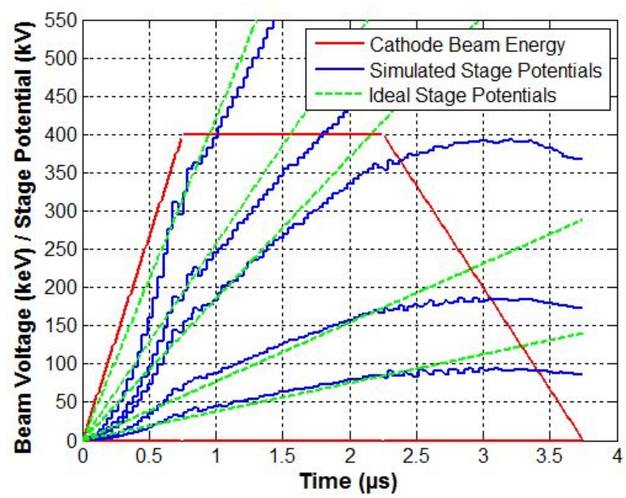


**Figure 2.** Example beam voltage (red) shown with ideal stage potentials (green) and simulated stage potentials for one approach to a five-stage depressed collector with the SLAC XL4 klystron.

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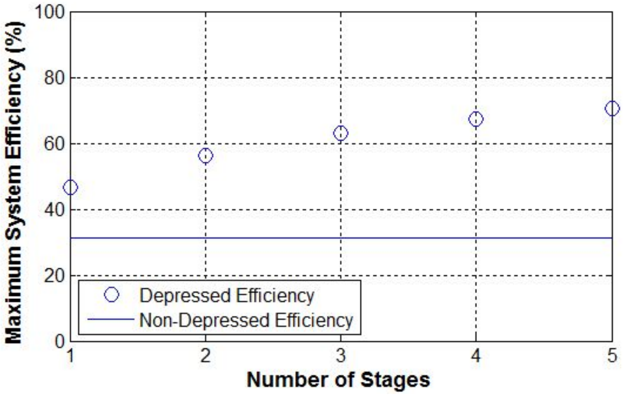


**Figure 3.** Maximum system efficiency versus number of stages for a SLAC XL4 system.

klystron rise and fall times in addition to the flat top. This greatly reduces the demands on the modulator. Second, the potentials can be externally "tuned" by adjusting the storage capacitance. Various gains or operating points can still be efficiently utilized. Third, there is a mechanism to recover electrons into the collector with a kinetic energy higher than the initial beam voltage. Fourth, existing systems can be retrofit with the design. The perveance of the tube and therefore modulator can remain the same. With a retrofit collector and new tap into the modulator, the majority of existing RF stations can be effectively upgraded to higher-efficiency systems. Fifth, this concept is not limited to a certain topology modulator. Solid state, PFN, Marx, and induction modulators all can incorporate this energy recovery.

## Calculated Impact

Case studies were conducted for two existing SLAC klystron systems. A circuit model of the transformer and its associated parasitics was coupled with a storage capacitor and an idealized current collection scheme (ie, no backscattering and electrons are captured by the next-lowest potential stage). The energy distribution for each klystron was generated from 1D PIC simulations for a given gain level. The stage potentials shown in Figure 2 are for one optimization run with five stages. The maximum anticipated system efficiency for various numbers of stages is given in Figure 3.

A collector geometry was created within a 2D PIC code. Using a time-varying beam energy profile and time-varying stage potentials, the current collected at each stage was measured. These currents were input to the transformer circuit model and the resulting stage potentials were measured. This process was iterated until convergence. Secondary electron effects as well as backscattering were included in the model. A collector efficiency of >55% was demonstrated. This efficiency will rise after conducting further optimizations of the collector geometry using published techniques [4]. Preliminary results for two different klystron systems are shown in Table 1. This is simulated efficiency using a five-stage, un-optimized collector.

**Table 1.** Calculated improvements in system efficiency for two SLAC klystrons.

| | **XL4** | **5045** |
|---|---|---|
| **Peak Power (nom.)** | 50MW | 58MW |
| **Klystron efficiency** | 41% | 45% |
| **System Efficiency (no recovery)** | 29% | 37% |
| **Depressed Collector Efficiency (assumed)** | 55% | 55% |
| **System Efficiency (with recovery)** | 50% | 57% |
| **Collector Power (no recovery)** | 22 kW | 41 kW |
| **Collector Power (with recovery)** | 8.8 kW | 16 kW |

## Conclusion and Next Steps

This paper presented the concept of a pulsed depressed collector for improving system efficiency for pulsed RF sources. This has the opportunity to be an enabling technology for high repetition rate systems. In addition, in systems where energy efficiency is at a premium, this concept can be used to retrofit existing hardware.

The next steps for this project include specifying the power converter for transferring the energy from the storage capacitor the modulator as well as specifying the pulse transformer. Following optimization of the collector geometry, a collector will be fabricated and fit to an existing klystron.


## Acknowledgements

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