SLAC-PUB-15964

A Self-Biasing Pulsed Depressed Collector

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***Abstract*—Depressed collectors have been utilized successfully for many years to improve the electrical efficiency of vacuum electron devices. Increasingly, pulsed, high-peak power accelerator applications are placing a premium on electrical efficiency. As RF systems are responsible for a large percentage of the overall energy usage at accelerator laboratories, methods to improve upon the state of the art in pulsed high power sources are desired. This paper presents a technique for self-biasing the stages in a multi-stage depressed collector. With this technique, the energy lost during the rise and fall time of the pulse can be recovered, separate power supplies are not needed, and existing modulators can be retrofitted. Calculations show that significant cost savings can be realized with the implementation of this device in high-power systems. In this paper, the technique is described along with experimental demonstration.**

***Index Terms*—Electron Tubes, High-voltage techniques, Klystrons, Pulse transformers, Pulsed power supplies, Pulsed power systems.**

I. Introduction and Motivation

THE PERFORMANCE of RF systems is increasingly critical in determining the cost and performance of RF accelerators. SLAC National Accelerator Laboratory (SLAC) has played a leadership role in the development and implementation of these systems for over fifty years. While this history has stimulated commercialization of many RF components and systems, the opportunity is now ripe for wholesale improvements upon the present state of the art.

Accelerator laboratories in the US use as much as 4 TW-hrs of energy a year. In addition to being costly to operate, there is political and public pressure to conserve energy while still pursuing the science goals of the laboratories [1]. In the case of one proposed high energy physics accelerator, CLIC, a primary limit to the proposed machine's size is the RF power system dominated, AC power consumption [2]. At SLAC, over 38% of the total laboratory's energy consumption is attributed to the RF systems.

Development of energy efficient RF systems directly addresses a recent presidential mandate. Executive order 13514 released in late 2009 requires 28% greenhouse gas reduction at federal research facilities [3]. As RF systems have a very large impact on the site power usage at SLAC and other facilities, improving their efficiency will have an impact on reducing greenhouse gasses, and therefore directly address the presidential mandate. Not only large accelerator laboratories benefit from improved RF systems. A recent DOE report identified RF sources as a very high priority for applications in industry, energy and the environment, defense and security, and discovery science [4].

Depressed collectors are one method to improve vacuum electron device efficiency. The longevity of collector development is certainly apparent when one considers that a "modern" review of the technology was published over thirty years ago [5]. However, widespread utilization of this technology for high energy accelerator applications is absent, although there have been paper studies on the potential application [6][7][8]. High peak power, low-bandwidth tubes common to accelerator applications have not been substantially optimized.

Many accelerator applications utilize pulsed, high peak power RF systems with duty cycles less than 1%. Typically, a

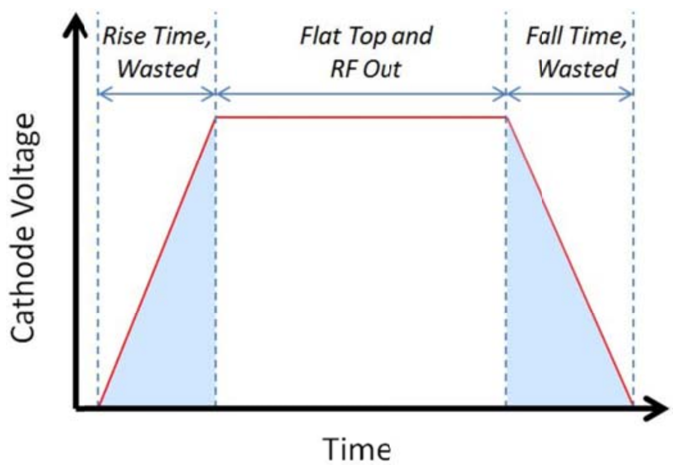

Fig. 1. A typical pulse shape of the applied voltage applied to the klystron cathode. The shaded areas represent unusable energy and are therefore, without a depressed collector, lost.

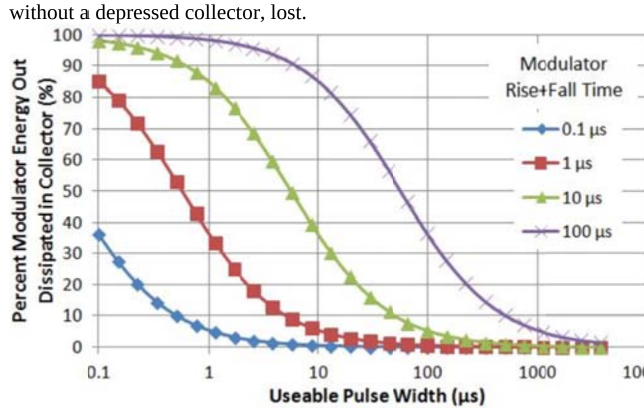

Fig. 2. Graph of the percentage of energy out from the modulator dissipated in a conventional, grounded collector during the rise and fall times of the pulse.

Manuscript submitted 10/31/2013. Work supported by Department of Energy contract DE-AC02-76SF00515.

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Work supported in part by US Department of Energy under contract DE-AC02-76SF00515.

high voltage, pulsed modulator delivers a pulse to the cathode of a klystron. A pulse shape, with rise, flattop, and fall times can be defined as in Fig. 1. Because accelerator applications require high RF phase stability during the pulse, the low level RF input is only applied during the high voltage modulator pulse flat top. Therefore, all of the beam energy during the modulator rise and fall times is wasted and is dissipated as heat in the klystron collector. Fig. 2 shows the amount of energy wasted in the collector for various rise and fall times. This is significant for short pulse, low duty cycle systems. In the case of the SLAC 5045 RF station, 10-20% of the energy exiting the modulator is wasted during the rise and fall time. Typical operating parameters for the 5045 tube are shown in Table I. For very short pulse applications, this problem is compounded: fast rise and fall times are very hard to achieve in high power modulators.

TABLE I. TYPICAL PARAMETERS FOR TWO SLAC KLYSTRONS.

	SLAC 5045	**SLAC Subbooster**	
RF Efficiency		45%	30 %
Beam Voltage		350 kV	25 kV
Perveance		2 µP	2.6 µP
Average Output RF Power		41 kW	25 W
Peak Output RF Power		65 MW	65 kW
RF Pulse Width		3.5 µs	3.5 µs
Pulse Repetition Frequency		180 Hz	120 Hz
Output Frequency		2.856 GHz	2.856 GHz

To present an alternative to conventional stage biasing approaches, a self-biasing, pulsed depressed collector technique was developed [9][10]. This technique is described in the following section. After, an experimental test of the concept is presented. The experimental results are then compared to a Particle in Cell (PIC) and circuit model. Finally, the implications of the results on future potential LCLS upgrades are discussed.

II. DESCRIPTION OF THE SELF-BIASING TECHNIQUE

Depressed collectors in RF amplifiers are a mature and successful technology for efficiency-critical applications such as space applications and UHF broadcast [11][12][13]. They are typically employed in low power CW tubes and function by extracting energy from the spent electron beam. One or more conductive stages are biased at negative electrical potentials below the kinetic energy of the beam. As the beam travels through the depressed collector, the electron momentum decreases until collected by a stage. Ideally, the momentum is reduced to zero just as it impacts a collector stage. Effectively, depending upon the stage biasing topology, a portion of the beam power is recovered to some point within the driving modulator/power supply, resulting in a reduced AC power draw. Reduced power draw with the same RF power out results in a higher system efficiency [14]. Depressed collectors have been applied to traveling wave tubes (TWTs) [13], gyrotrons [15][16], klystrons [17], and inductive output tubes (IOTs) [18][19].

With a pulsed, high-power system, utilization of a depressed collector to increase system efficiency is not straightforward. The conventional method for applying a pulsed potential to a collector stage is to tap off of the secondary of the output transformer of the modulator [20]. While appropriate for some applications, this approach is not viable for many accelerator applications: it can cause deleterious cathode voltage ringing due to parasitic impedances. This ringing translates into RF phase jitter and unacceptable performance.

To solve this issue, the newly developed "pulsed depressed collector", shown in Fig. 3, utilizes a step-down transformer and capacitor to recover energy by dynamically biasing the potentials of a multi-stage depressed collector. At the beginning of the pulse, the potentials of all the stages start at zero voltage. As the spent beam impacts the stages, the stages charge up. The time-varying potential of each collector stage is determined by the current collected by the stages as well as the effective impedance of the step-down transformer and

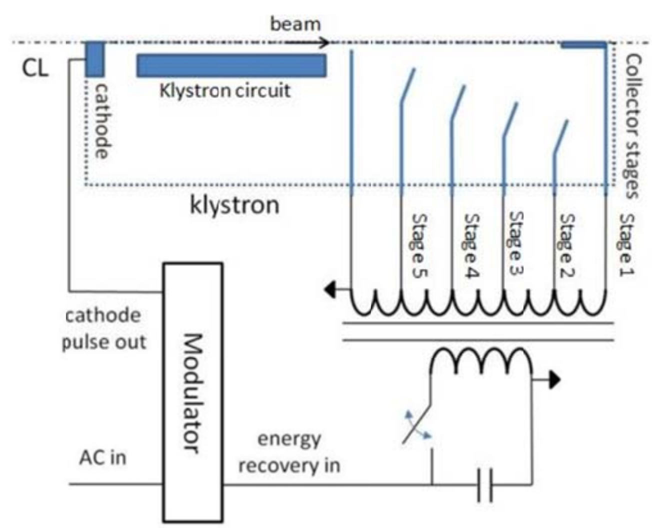


Fig. 3. Schematic of the pulsed depressed collector klystron, biasing network, and modulator interface.

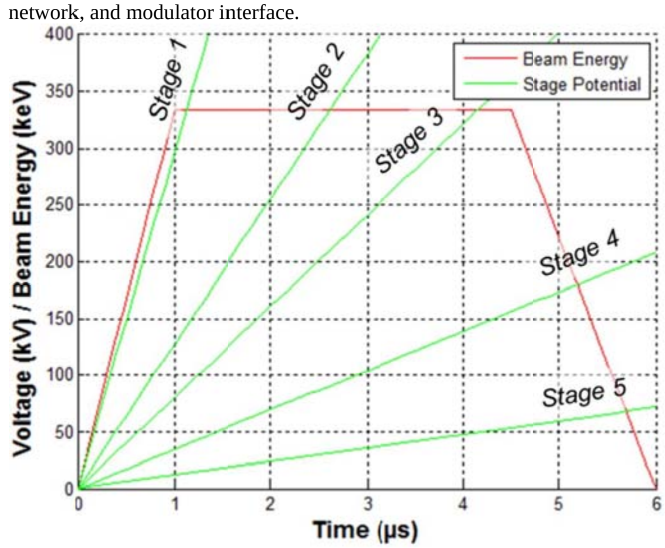


Fig. 4. The klystron initial electron beam energy (red) and the resulting collector stage potentials versus time (green).

storage capacitor. A simplified charging scheme is shown in Fig. 4. Here the potentials rise linearly, while in practice, the slopes will change over time and level off. After the pulse, the energy from the storage capacitor is recovered back to the modulator for use in the subsequent pulse.

This concept has several advantages. First, the energy during the rising and falling edge of the pulse is recovered. This reduces the burden on the modulator to produce very fast pulse edges, thereby simplifying the design and cost. Second, existing systems can be retrofitted. The modulator provides the same output pulse as it would have without the depressed collector. Because a second transformer is utilized, the depressed collector is effectively decoupled from the driving modulator. Cathode ringing is not possible. Third, additional high voltage bias supplies are not necessary since it is self-biasing. This lessens the expense of adding additional collector stages. In addition, availability should increase because of the reduced number of power components.

III. Experiment and Model

To demonstrate the self-biasing concept, a pilot study was conducted. The goals of the study were to illustrate the ability to control the biasing of the stages via an external impedance and experimentally validate the models. To quickly achieve these goals, an existing SLAC subbooster klystron was modified with a two stage depressed collector. For simplicity, all results shown here only utilize a single stage. The purpose of the study was not necessarily to maximize collector efficiency, but to use the klystron as a test platform for the pulsed depressed collector concept. The subbooster parameters are given in Table I, and a drawing and photograph of the modified klystron are shown in Fig. 5.

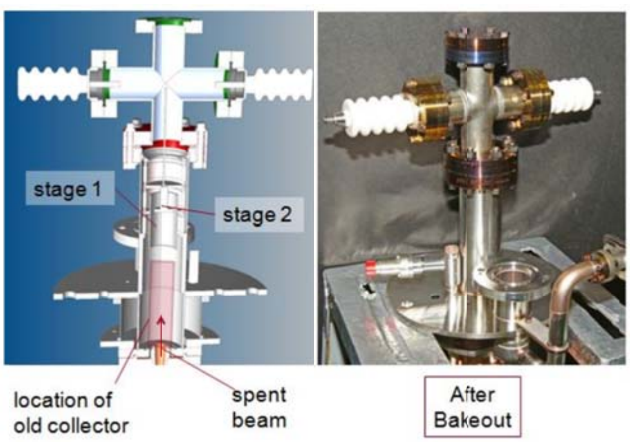


Fig. 5. Multistage depressed collector added to the existing SLAC subbooster klystron. (left) 3D drawing cutaway showing the beam direction and location of old collector. (right) Photograph of completed unit.

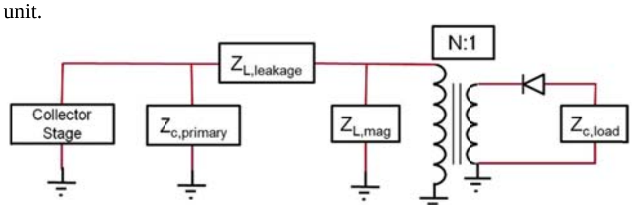


Fig. 6. Simplified circuit model of the stage biasing network. Parasitic elements in the transformer act as reactive impedances to shape the transient behavior of the stage.

The subbooster klystron was chosen as a test platform for several reasons. First, the beam voltage, -25kV, is relatively low and can easily be measured in open air with standard commercial probes. Second, a test stand for the klystron already existed. And, third, many of these klystrons and their associated hardware were readily available in the laboratory.

The biasing impedances used in the experiment are shown in Fig. 6. Although they are not all completely independent, the values can be easily altered to quantify the effect on collector efficiency. For example, the load capacitance can be swept over a range of values.

Example results from the experiment are shown in Fig. 7. A rising stage potential that reaches a maximum voltage of -15 kV is achieved. Changing the biasing impedances also changes the shape and magnitude of the stage potential, as shown in Fig. 8. In contrast to the simple straight line biasing shown in Fig. 4, a more efficient collector results from a “square” biasing waveform as shown by “Stage Tuning 1” in Fig. 8. These experimental results demonstrate the ability to control the stage biasing via external passive impedances.

The second purpose of this study is to demonstrate the ability to effectively model the system. A particle-in-cell (PIC) code was used to model the subbooster klystron from cathode to collector. The stage currents were exported to SPICE and used as current sources into the circuit model of the biasing

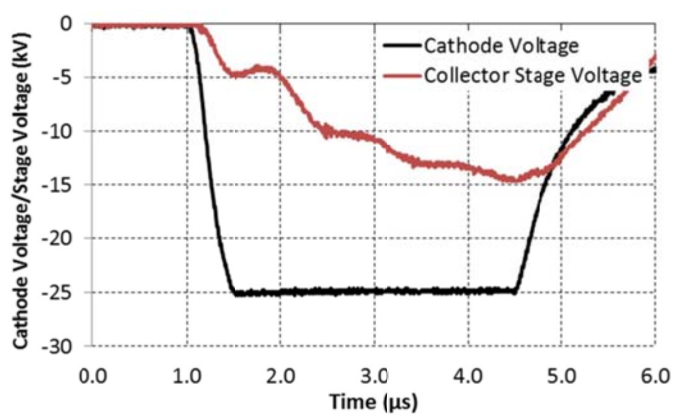


Fig. 7. Measured cathode voltage and the measured stage potential for a typical experiment.

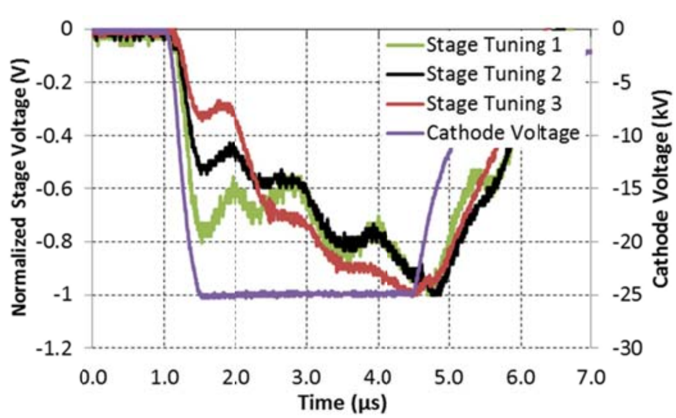


Fig. 8. Measured cathode voltage and three example normalized stage potentials. Shown is the ability to shape the stage potential by adjusting the biasing network impedance.

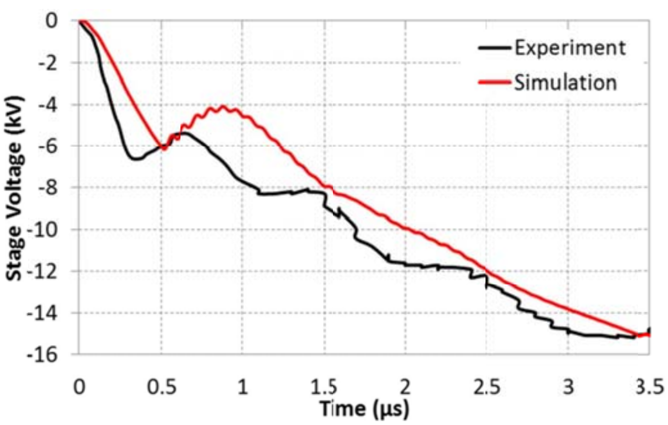
network. All circuit elements except for the transformer loss terms were derived or measured separately. The resulting stage potential from SPICE was then input to the PIC code, and once again the resulting stage currents were obtained. This was repeated until convergence. The transformer loss term was fit using several experimental biasing conditions.

Figure 9 shows a comparison of the simulations to the experimental data for two variables of interest. In general, good agreement is obtained. Using the measured and simulated load capacitance voltage at the end of the pulse, the recovered energy is calculated. This is used to calculate the collector efficiency, eq. (1). The measured versus simulated results are shown in Table II. Several different biasing conditions all show good agreement.

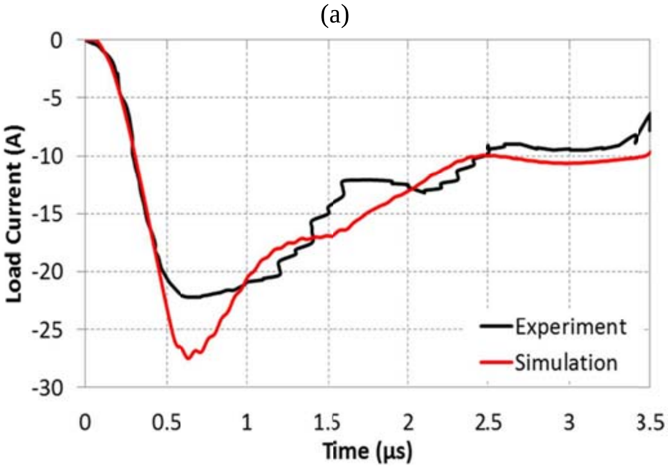
$$\eta_{collector} = \frac{E_{recovered}}{E_{spent,beam}} \% \tag{1}$$

TABLE II. EXAMPLE COMPARISON OF SIMULATED COLLECTOR EFFICIENCY COMPARED TO EXPERIMENTALLY MEASURED COLLECTOR EFFICIENCY.

	Biasing Impedance/ Stage Voltage Maximum		
	22 nF/15kV	*44nF/11kV*	*66nF/9kV*
Measured	18%	19%	17%
Simulated	20%	19%	18%



(a)



(b)

Fig. 9. Comparison of transient model versus experiment for two different traces of interest, (a) the stage voltage and (b) the load current.

IV. PROJECTED PERFORMANCE

The PIC and SPICE model presented above is for an existing klystron and collector geometry. To estimate the usefulness of the self-biasing depressed collector on unrealized klystrons and collectors, a Matlab script was authored. It models the effect of changing the biasing waveforms or adding stages when given only the spent beam energy distribution. An effective secondary electron emission coefficient and a collector "geometry factor" are assumed. The geometry factor is effectively a measure of how well the depressed collector optics are designed. This is implemented in the Matlab code by requiring a particle to have a kinetic energy of at least the potential of the stage divided by the geometry factor to be collected; otherwise it is rejected to the next lower potential stage. With this simple model, tradeoffs can be calculated for various biasing schemes, spent beam energy spreads, or numbers of stages.

This Matlab script is run to benchmark the subbooster klystron experiments described above. The resulting calculated collector efficiency versus various geometry factors is shown in Fig. 10. As shown, the blue curve matches the measured and modeled data in Table II. Therefore, one might assume the effective geometry factor for the depressed collector as implemented is 0.8.

This same model is used to predict the achievable collector and klystron efficiency for a SLAC 5045 klystron. Using constant slope, time varying stage potentials, the potential

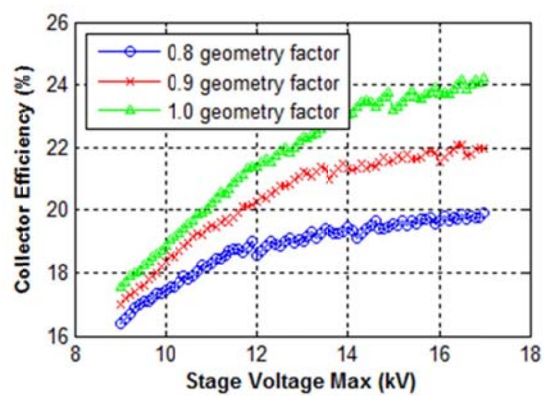


Fig. 10. Simulated *subbooster* klystron collector efficiency for various geometry factors. As shown, a geometry factor of 0.8 matches the measured collector efficiency data in Table II.

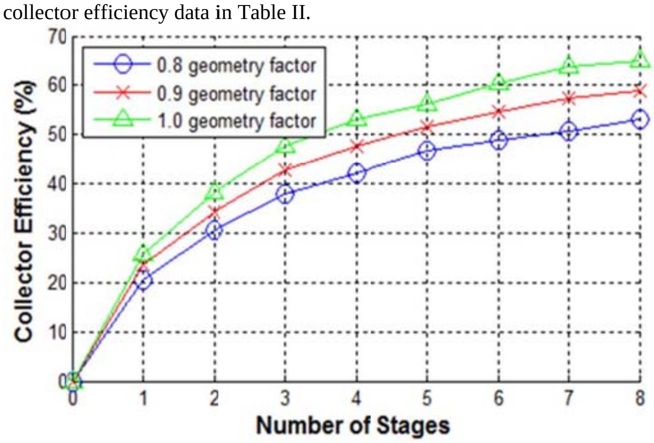


Fig. 11. Simulated *5045* collector efficiency versus the number of collector stages.

magnitudes are swept to find the maximum efficiency. The collector efficiency for various numbers of stages and assumed geometry factors are shown in Fig. 11.

Assuming a 0.8 geometry factor collector can be achieved, as it was in the un-optimized experiment presented above, the pulsed klystron efficiency can be improved from the baseline 40% to greater than 65% with five collector stages. If a non-constant stage potential slope is assumed (i.e., a shaped bias as demonstrated in Fig. 8), the achievable total pulsed klystron efficiency is greater than 70%.

The impact of including a 5045 klystron with a depressed collector in the existing SLAC RF station can be estimated. Defining the total RF station efficiency to be RF power out over AC power in, Table III shows the reduction of waste heat per station. As shown, 25 kW less average power is consumed per station, a reduction of 31%. Note that these calculations conservatively assume a certain collector de-rating, the existing modulator transfer efficiency, and a 0.8 collector geometry factor, which limits the ideal collector efficiency. Even so, a 25 kW power reduction would result in a $10k/year reduction in power costs for a typical LCLS station. If implemented for all 80 stations in LCLS, this would result in a substantial savings of $800k/year. Additional cost savings would result from secondary systems such as cooling towers and water pumps.

TABLE III. CALCULATED POWER REDUCTION BENEFITS OF USING A PULSED DEPRESSED COLLECTOR IN A RETROFIT SLAC 5045 RF STATION.

	Existing SLAC Station	**Retrofit Station**
Klystron RF Efficiency	0.45	0.45
Collector Ideal Efficiency	0.00	0.75
Overall System Efficiency	0.25	0.33
Avg RF Out (kW)	27	27
AC in (kW)	107	82
Waste Heat Per Station (kW)	80	55

V. CONCLUSION

A self-biasing pulsed depressed collector technique has been presented. The experimental results demonstrate the ability to control stage biasing via external impedances and recover a portion of the beam energy. This technique is an enabling technology for high-efficiency pulsed RF systems. Future work will involve scaling the technique to a high power tube such as the SLAC 5045.

ACKNOWLEDGMENT

The Authors acknowledge David Martin for the mechanical design of the subbooster depressed collector. Eric Jongewaard, Andy Haase, Michael Fazio, and Craig Burkhart provided helpful suggestions. The SLAC Vacuum Microwave Devices Department provided critical fabrication and testing services.

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