A 71 dB Gain, High Efficiency Relativistic Klystron using a High Current Linear Accelerator Traveling Wave Buncher Output Structure

J. Haimson and B. Mecklenburg

Haimson Research Corporation
3350 Scott Blvd., Bldg. 60, Santa Clara, CA 95054-3104, USA

Abstract. After five years of operation, the 17 GHz MKII relativistic klystron in service at the MIT Plasma Science and Fusion Center was upgraded with a new output structure to provide a common source of high peak power for continuing operation of the 17 GHz linac, for RF gun testing and for energizing a recently developed circularly polarized beam deflection RF system to evaluate the ultra short electron bunch performance of the linac.

The salient features of the impedance and phase velocity tapered new traveling wave output structure designed for high gain and stability are described; and initial high power test results of the 17 GHz relativistic klystron are presented. The output structure was designed as a beam driven bunching and phase shifting 2\pi/3 mode circuit using codes that were developed over a 40 year period designing, fabricating and testing high current traveling wave linac bunchers.

The electrical length of the new (MKIII) output circuit was extended to 1200 degrees using a group to phase velocity harmonic mean ratio of 0.124 to provide total skin losses of less than 5 percent and a phase/frequency sensitivity of only 0.6 degree/MHz. A dual feed racetrack shaped output cavity having a decelerating gradient of 150 kV/cm and beam apertures substantially larger than \lambda_o/2, to allow reduction of space charge debunching forces, are added advantages of this 25 MW, 71dB gain RF amplifier.

INTRODUCTION AND BACKGROUND

A detailed description of the prototype version of this horizontally oriented, vacuum demountable, traveling wave relativistic klystron (TWRK) and the associated precision aligned solenoid assembly has been presented elsewhere [1]. The prototype TWRK microwave circuit extended over a 42 cm distance and comprised a drive cavity, two gain cavities, two inductively tuned prebunching cavities and a 2\pi/3 mode tapered phase velocity TW output structure. The electron source is a 550 kV, 0.25 microperveance diode electron gun driven by a high voltage, line type modulator [2]. Two modifications were made to the prototype tube after it was initially placed into service. A MKI modification converted the original single feed cylindrical output cavity into a dual output racetrack shaped cavity [3]; and a MKII modification resulted in the integration of a beam centerline high vacuum demountable joint at entry to the
TW output structure, and the suppression of a spike-like 21 GHz oscillation that was especially evident when the tube was operated into a mismatched load.

During the past five years, the MKII TWRK has provided RF power for both a 17 GHz linac system [4] (that includes a 550 kV chopper/prebuncher injector [5]) and a high power test stand designed for RF gun experiments [6, 7]. A multiple hybrid, evacuated rectangular waveguide network, incorporating high power RF windows, phase shifters and high directivity directional couplers, enables power from the klystron output arms to be combined and then transmitted to both test stations at remotely controlled amplitude levels. Power from the 17 GHz klystron is also required for several new projects, including two ultra short bunch diagnostic experiments [8, 9] and the testing of a photonic band gap (PBG) 2π/3 structure [10], as illustrated below in the Fig. 1 block diagram.

Because of the growing number of experiments and the increasing dependence on this sole 17 GHz high power source, consideration was given to fabricating a standby dual feed TW output structure that could be conveniently retrofitted as a replacement spare. Thus, an opportunity was presented to explore means of further enhancing the klystron performance. Due to space charge related limitations imposed on short wavelength high power klystrons, only a small improvement of the existing 50 percent efficiency could be expected. However, a high gain demonstration of, say, 70 to 75 dB with a relativistic klystron would be of significant value, especially for multiple klystron linac applications. A high gain performance would also be beneficial for the

![Block diagram](image)

**FIGURE 1.** Block diagram illustrating the growing array of experiments receiving RF power from the 17 GHz TWRK at the MIT Plasma Science and Fusion Center.
single klystron application at MIT, since it would enable the existing relatively complex TWT driver and associated pulsed helix and filament power supplies to be replaced with a simple, very compact 17 GHz solid state source. Thus, the standby output structure (MKIII) was designed as a high gain, extended interaction TW bunching circuit using the multi-orbit time domain simulation codes PRELORA and ELORA [4, 11] originally developed for high current, disc loaded TW linac bunchers.

**GAIN AND SPACE CHARGE CONSIDERATIONS**

To increase the gain, the MKIII TW output structure was designed to have a longer interaction length and a lower impedance than the MKII circuit, and, consistent with operation at a lower drive power, the phase acceptance was increased to accommodate a reduced momentum spread beam. Increasing the interaction length enables a near adiabatic, gradual bunch compression to be achieved by maintaining cross-over free, laminar phase orbits as the circuit phase velocity and impedance are progressively reduced. The reduced impedance compensates for the longer interaction length, conserves $\int E_z dz$ and avoids loss of RF output power due to phase slip and premature beam acceleration. Progressive adjustment of the circuit phase velocity not only allows a near synchronous interaction to be maintained as energy is extracted from the beam, but also provides phase control so that the field gradient across the bunch can be maximized to counteract the increasing space charge debunching forces.

Typical 17 GHz TWRK space charge longitudinal electric field distributions during bunch formation in the drift space region between the penultimate cavity and the output structure are shown in Fig. 2. For the listed beam parameters, the data indicates that, with approximately 75 percent of the beam charge (4nC) contained in a $\Delta \omega t = 80^\circ$ bunch, the space charge debunching gradient is approximately 90 keV/cm.

The beam momentum spread produced by the two inductively tuned prebuncher

![FIGURE 2. Temporal and spatial distributions of space charge longitudinal electric field in the drift space at entry to the output structure.](image)
cavities is sufficient to overcome this gradient for a short distance after entering the low gradient region of the TW output structure. Thereafter, continuation of the bunching process (and increasing the gain) is dependent on the growing induced circuit field overcoming the growing space charge gradient.

Before detailed design simulations are performed, the magnitude of the bunch space charge fields inside the TW structure during the deceleration process can be readily estimated from simple bunch models to ensure that the initial selection of TW cavity shunt impedance and loss values will result in a sufficiently large circuit gradient. For example, with a 17.136 GHz TW circuit entry phase velocity of 0.9c, an injected 6 mm diameter, 68° bunch will have a length of 3 mm in the laboratory frame. Thus, for an entry beam energy of 511 kV (γ = 2.0), the rest frame bunch will have the form of a 6 mm diameter sphere. For both of the charge density distributions defined in the Appendix, the space charge longitudinal electric field (Ez) at the terminal point (z/c = 1) of a sphere of radius (a) is related to the bunch charge (Q) by the unitless expression, 4πa²ε₀Ez/Q = 1.0; and for a bunch charge of, say, 4nC, the above injected bunch will have terminal radial and longitudinal space charge fields of approximately 40 kV/cm. Thus, with an initial energy modulation of approximately 200 keV, bunching will continue for a short distance along the structure; and, thereafter, the bunching process will be maintained by the growing 100-150 kV/cm circuit gradient.

With progression along the TW circuit, unlike a linac buncher where an initial sphere shaped electron bunch is transformed by acceleration into a prolate spheroid, deceleration in a klystron output structure causes a spherical bunch to transform into an oblate spheroid with high Er and Ez space charge fields, as illustrated in the Appendix. As an example, consider a decelerated electron bunch with a remnant beam energy of, say, 80 kV traversing the exit region of a TW output structure having a reduced phase velocity of, say, 0.76c. In the rest frame, a 70° bunch will be 3 mm long; and with an unchanged beam diameter, the bunch will take the form of an oblate spheroid having a semi-axis ratio a/c = 2. For this case, the Appendix oblate spheroidal bunch data gives the Ez terminal field as 4πa²ε₀Ez/Q = 1.6 (to 1.9), depending on the charge density distribution; and assuming conservation of the 4nC charge, the terminal Ez field will be intensified to a value of 64 (to 76) kV/cm. This space charge field intensification can be effectively avoided, however, if the above discussed reduction in circuit impedance is obtained by progressively increasing the beam apertures (and reducing the phase velocity) so that a 50 percent increase in beam diameter can be tolerated without danger of interception. The Appendix data indicate that the resulting a/c = 3 rest frame oblate spheroidal geometry will cause the bunch terminal Ez field to be reduced to approximately 35 kV/cm, thereby enabling enhanced bunching to be achieved.

The Traveling Wave Advantage

Because of a fundamental difference in field propagation characteristics, a TW output structure can be considerably more effective than a SW structure in controlling high space charge debunching forces to achieve tighter bunching and a higher gain performance. In a coupled cavity SW circuit, even for optimally phased electron bunches, the circuit field gradients, counteracting the space charge debunching forces,
are repetitively removed and reapplied every half RF cycle during the full beam trajectory. In a coupled cavity TW output structure, however, the fundamental space harmonic and associated higher order field components enable all near-synchronous particles to experience a continuous bunching (and decelerating) gradient. This is especially the case with large aperture, reduced phase velocity output circuits because the amplitude of the fundamental space harmonic is >90 percent of the total field peak value, and because the total field envelope has little variation between the maximum and minimum values that occur at the cavity and disc midplanes, respectively, due to the aligned higher order space harmonic vectors adding or subtracting from the fundamental [11]. The time averaged profiles of SW and TW axial electric field distributions are shown in Fig. 3 for disc loaded cavities typically used in Haimson Research 11.4 and 17.1 GHz relativistic klystron output structures. The noticeable absence of phase dwell at the cavity midplanes results from the use of a very high group velocity (refer Table 1). Figure 4 shows a simulation of the propagating $2\pi/3$ mode electric field, and its coalescence with the SW field in the output cavity.

![FIGURE 3. Comparison of standing and traveling wave field distributions in a 2π/3 mode, large beam aperture, reduced phase velocity circuit.](image1.png)

![FIGURE 4. Frozen video image revealing the propagation pattern of the 2π/3 mode TW electric field and its coalescence with the SW field in the output cavity.](image2.png)
OUTPUT CIRCUIT DETAILS

The design parameters of the MKIII output structure are shown listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traveling Wave Operating Mode</td>
<td>$TM_{01}, 2\pi/3$</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>17.136 GHz</td>
</tr>
<tr>
<td>Free Space Wavelength</td>
<td>17.495 mm</td>
</tr>
<tr>
<td>TW Electrical Length</td>
<td>1200 deg.</td>
</tr>
<tr>
<td>Group Velocity Range</td>
<td>0.085 c to 0.119 c</td>
</tr>
<tr>
<td>Harmonic Mean Group Velocity</td>
<td>0.097 c</td>
</tr>
<tr>
<td>Filling Time</td>
<td>1.73 ns</td>
</tr>
<tr>
<td>Harmonic Mean Ratio of Group to Phase Velocity</td>
<td>0.124</td>
</tr>
<tr>
<td>Output Phase/Frequency Sensitivity</td>
<td>0.6 deg/MHz</td>
</tr>
<tr>
<td>Output Phase/Temperature Sensitivity</td>
<td>0.17 deg/°C</td>
</tr>
<tr>
<td>Attenuation Parameter</td>
<td>0.023 Np</td>
</tr>
</tbody>
</table>

Following the successful long term operation of the MKII output structure having imbedded stainless steel iris apertures brazed into the first three copper discs [12], the MKIII circuit was also fabricated with this beam interception safety and HOM damping feature. A 3-D illustration of the MKIII output structure is shown in Fig. 5. This view clearly shows the increasing cavity diameters, indicative of the progressively increasing beam apertures and decreasing phase velocities. The racetrack shaped, dual feed output cavity can also be noted extending above the periphery of the contiguously located cylindrical cavity.

Figure 6 shows a view of the klystron output structure and the dual WR62 rectangular waveguide arms after completion of the final braze in a dry hydrogen furnace. The assembled klystron centerline components, including the MKIII structure, water interconnections and the solenoid alignment fixtures, are shown in Fig. 7, with the removed MKII output structure shown in the background.

FIGURE 5. 3-D model of the high gain 17 GHz TWRK MKIII output structure featuring the $2\pi/3$ mode progressively reduced phase velocity cavities and the dual feed racetrack shaped output coupler.
HIGH POWER RF SYSTEM AND TEST RESULTS

Each klystron output arm was connected to an evacuated WR62 rectangular waveguide network having a VSWR of not greater than 1.5 over a band width of 800 MHz; and each network comprised two high conductance pumping ports, a high directivity directional coupler and a ceramic window water load. Figure 8 shows the high power klystron test stand during rough-out of the waveguide vacuum system.
Because all the waveguide components, including the high vacuum pumps, are mounted and aligned on a linear bearing supported platform that can be rolled aside, the klystron can be readily accessed and extracted from the solenoid. This feature, combined with the centerline demountable flanges, enables the klystron components to be conveniently interchanged and high power tested.

The klystron was beam processed initially without RF, using 1 μs pulses up to 545 kV; and a stable zero drive performance was demonstrated with the collector current free of glitches or oscillations. Typical klystron voltage and collector current waveforms are shown in Fig. 9. The RF processing commenced with short (50 ns), low amplitude drive pulses and a reduced gun voltage, and proceeded with slowly increasing drive pulse widths. The Fig. 10 diode waveforms show the klystron power from output arms A & B for a 400 ns wide drive pulse at 17136 MHz, with the tube operating at 475 kV and with high settings of the solenoid magnet currents. Under these conditions, with 7½ MW in each arm, the gain of the klystron was 69 dB.

![FIGURE 9. Typical klystron voltage and collector current waveforms with zero RF drive.](image)

![FIGURE 10. Waveforms of the RF drive and collector current with 400 ns pulse operation at 17136 MHz and 475 kV.](image)

The klystron output power response was noted to be quite sensitive to small adjustments of low current settings in the last solenoid winding (module #6) controlling the axial magnetic field at the end of the TW output structure. A plot of klystron output power versus the current in solenoid module #6, with all the other solenoid settings held constant, is shown in Fig. 11. The data indicate that the klystron output power increases by more than 15 percent for an increase in beam diameter of approximately 30 percent, presumably due to the combined effects of the higher off-axis field gradients that are present in reduced phase velocity cavities, and the enhanced bunching associated with the larger beam diameter reduced space charge forces.
A typical klystron output waveform during operation at a beam voltage of 535 kV and a gain of 71 dB is shown in Fig. 12; and the MKIII TWRK test results obtained at a beam voltage of 545 kV are listed in Table 2.

![Klystron Output Waveform](image)

**FIGURE 11.** Klystron output power dependence on axial magnetic field at the TW structure exit.

**FIGURE 12.** Klystron RF output waveform during operation with a gain of 71 db at 535 kV and 17136 MHz.

**TABLE 2.** Test Results Obtained with the MKIII TWRK.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Gun Voltage</td>
<td>545 kV</td>
</tr>
<tr>
<td>Collector Current</td>
<td>91 A</td>
</tr>
<tr>
<td>Electron Beam Power</td>
<td>50 MW</td>
</tr>
<tr>
<td>Drive Frequency</td>
<td>17136 MHz</td>
</tr>
<tr>
<td>Drive Pulse Width</td>
<td>100 ns</td>
</tr>
<tr>
<td>Drive Cavity Input Power</td>
<td>1.8 W</td>
</tr>
<tr>
<td>Output RF Power</td>
<td>25.5 MW</td>
</tr>
<tr>
<td>RF Conversion Efficiency</td>
<td>51 %</td>
</tr>
<tr>
<td>Saturated Gain</td>
<td>71.5 dB</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

A saturated gain of 71.5 dB was demonstrated with an 11 cell 2π/3 traveling wave buncher output structure having a conversion efficiency of 51 percent while operating at a beam voltage of 545 kV with the klystron output arms terminated in broadband RF water loads having a maximum VSWR of 1.5.

The research capability of this 17 GHz high power test facility would be further enhanced by the development of high power isolators or RF filter/circulators that would enable the TWRK to operate safely into high VSWR mismatched experimental systems, and by replacement of the existing TWT driver system with a simple solid state amplifier.

**ACKNOWLEDGMENTS**

The authors wish to acknowledge the dedicated efforts of their colleagues during the design and fabrication stages of this project; and express gratitude to I. Mastovsky for assistance during installation and testing of the klystron, and to S. Korbly and A. Kesar for calibration of the RF diagnostics and assistance in data acquisition at MIT. This work was supported in part by the U.S. Department of Energy SBIR Program.
Space charge electric field components along the z and r-axes in a cylindrical coordinate system are shown plotted in unitless values in Fig. 13. Expressions for these field components for the illustrated idealized bunch geometry (oblate spheroidal, spherical and prolate spheroidal) and for two theoretical charge density distributions (uniform and spheroidal) centered at the origin of the coordinate system are given below.

**FIGURE 13.** Space charge electric field distributions for a total bunch charge $Q$.

**Space-charge Electric Field for Uniform Charge Density**

The total charge contained in a spheroid (with semi-axes $a$ and $c$ where rotation is around $2c$) having a uniform charge density distribution $\rho = \rho_0$ is $Q = \frac{4}{3} \pi a^2 c \rho_0$.

(a) **Oblate Spheroid** ($a > c$) – rotation around the minor axis, $2c$.

$$E_z(r = 0) = \frac{Q}{4\pi a^2 \varepsilon_0} \left(3\right) \left(\frac{z}{c}\right) \left(\frac{1+A^2}{A^2}\right) \left[1 - \frac{1}{A} \tan^{-1} A\right]$$

$$E_r(z = 0) = \frac{Q}{4\pi a^2 \varepsilon_0} \left(\frac{3}{2}\right) \left(\frac{r}{a}\right) \left(\frac{a}{c}\right) \left(\frac{1}{A^2}\right) \left[-1 + \frac{1+A^2}{A} \tan^{-1} A\right]$$

where $A^2 = a^2 / c^2 - 1$ and $\varepsilon_0 = \frac{1}{36\pi} \times 10^{-9}$ F/m in mks units.
(b) **Sphere.**

\[
E_z(r = 0) = \frac{Q}{4\pi a^2 \varepsilon_0} \left( \frac{z}{a} \right) \quad \text{and} \quad E_z(z = 0) = \frac{Q}{4\pi a^2 \varepsilon_0} \left( \frac{r}{a} \right)
\]

(c) **Prolate Spheroid** \((a < c)\) – rotation around the major axis, \(2c\).

\[
E_z(r = 0) = \frac{Q}{4\pi a^2 \varepsilon_0} \left( \frac{z}{c} \right) \left( 1 - \frac{A^2}{A^2} \right) \left[ -1 + \frac{1}{2A} \tan^{-1} \left( \frac{1 + A}{1 - A} \right) \right]
\]

\[
E_z(z = 0) = \frac{Q}{4\pi a^2 \varepsilon_0} \left( \frac{3}{2} \right) \left( \frac{r}{a} \right) \left( \frac{a}{c} \right) \frac{1}{A^2} \left[ -1 + \frac{1 - A^2}{2A} \tan^{-1} \left( \frac{1 + A}{1 - A} \right) \right]
\]

where \( A^2 = 1 - a^2 / c^2 \).

**Space-charge Electric Field for Non-uniform Charge Density**

For the spheroidal charge density distribution \( \rho = \rho_0 \left( 1 - r^2 / a^2 - z^2 / c^2 \right) \),

\[
Q = \frac{8}{15} \pi a^2 c \rho_0.
\]

(a) **Oblate Spheroid** \((a > c)\) – rotation around the minor axis, \(2c\).

\[
E_z(r = 0) = \frac{15Q}{8\pi a^2 \varepsilon_0} \left( \frac{z}{c} \right) \left\{ \left( 1 + \frac{A^2}{A^2} \right) \left[ -1 - \frac{1}{A} \tan^{-1} A \right] + \right.
\]

\[
\left. \frac{z^2}{c^2} \left( 1 + \frac{A^2}{3A^4} \right) \left[ 3 - A^2 - \frac{3}{A} \tan^{-1} A \right] \right\}
\]

\[
E_z(z = 0) = \frac{15Q}{8\pi a^2 \varepsilon_0} \left( \frac{1}{2} \right) \left( \frac{r}{a} \right) \left( \frac{a}{c} \right) \left[ \frac{1}{A^2} \left[ -1 + \frac{1 + A^2}{A} \tan^{-1} A \right] + \right.
\]

\[
\left. \frac{r^2}{a^2} \left( \frac{1}{4A^4} \right) \left[ 3 + 5A^2 - \frac{3(1 + A^2)^2}{A} \tan^{-1} A \right] \right\}
\]

where \( A^2 = a^2 / c^2 - 1 \).

(b) **Sphere.**

\[
E_z(r = 0) = \frac{15Q}{8\pi a^2 \varepsilon_0} \left( \frac{z}{a} \right) \left( \frac{1 - \frac{1}{5} \frac{z^2}{a^2}}{3} \right) \quad \text{and} \quad E_z(z = 0) = \frac{15Q}{8\pi a^2 \varepsilon_0} \left( r \right) \left( \frac{1 - \frac{1}{5} \frac{r^2}{a^2}}{3} \right)
\]
(c) Prolate Spheroid $(a < c)$ – rotation around the major axis, $2c$.

\[
E_z(r = 0) = \frac{15Q}{8\pi a^2 e_0} \left( \frac{z}{c} \right)^2 \left[ \left( \frac{1 - A^2}{A^2} \right)^2 - 1 + \frac{1}{2A} \ln \left( \frac{1 + A}{1 - A} \right) \right] + \\
\frac{z^2}{c^2} \left[ \frac{1 - A^2}{3A^4} \right] \left[ 3 + A^2 - \frac{3}{2A} \ln \left( \frac{1 + A}{1 - A} \right) \right]
\]

\[
E_r(z = 0) = \frac{15Q}{8\pi a^2 e_0} \left( \frac{1}{2} \right) \left( \frac{r}{a} \right)^2 \left[ \frac{r}{a} \right]^2 \left[ 1 - \frac{1 - A^2}{2A} \ln \left( \frac{1 + A}{1 - A} \right) \right] + \\
\frac{r^2}{a^2} \left( \frac{1}{4A^4} \right) \left[ 3 - 5A^2 - \frac{3(1 - A^2)^2}{2A} \ln \left( \frac{1 + A}{1 - A} \right) \right]
\]

where $A^2 = 1 - a^2 / c^2$.

REFERENCES


