USE OF TW OUTPUT STRUCTURES FOR HIGH PEAK POWER RF GENERATORS

J. Haimson and B. Mecklenburg

Haimson Research Corporation
4151 Middlefield Road • Palo Alto, CA 94303-4793

Abstract

The beam optics and electric field characteristics of several recently constructed TW structures are presented. These structures were designed to extract high levels of peak power from 11.4 GHz modulated, 500 to 1000A electron beams using three different RF amplifier configurations having nominal beam energies of 3.0, 1.2 and 0.5 MeV, respectively. The adoption of multicell, high phase velocity TW output circuits with unusually large beam apertures ($>\lambda_0/2$) has been instrumental in avoiding electric field breakdown and beam interception in these short wavelength, high current RF generators. For beam energies in the range of 0.45 to 1.3 MeV and RF output peak power levels of 100 to 300 MW, varying impedance and tapered phase velocity structures were used to minimize debunching and to maintain near synchronous conditions during beam traversal of the continuous interaction output circuit.

A concluding section discusses the design characteristics and performance of a new style 100 MW TW klystron specifically configured to operate in a small warm bore superconducting solenoid or a 4"ID water-cooled solenoid.

Introduction

The rationale for using TW output structures (a) to avoid RF breakdown at high levels of peak RF power, (b) to prevent beam interception when transporting large emittance, high current beams through short wavelength structures, and (c) to provide temperature and frequency insensitive, very fast response circuits (1 ns), has been presented elsewhere,[1] and this paper describes the reduction to practice of several high power TW output circuits designed for operation with three different combinations of beam energy and current, as listed in Table I below.

TABLE I. 11.4 GHz TW OUTPUT STRUCTURE APPLICATIONS

Application	Electron Source		I_{RF} (A)	Peak RF Output Power (MW)
	V_0 (MeV)	I_0 (A)		
TW Kly (X-791)	0.45-0.5	450-500	450-500	100
SL4/SHARK[2]	1.1-1.3	600-700	550-600	250-300
Choppertron[1]	2.7-3.0	1000	420-520	250†

†Design objective from each arm of a dual output system awaiting test.

All of the above RF generator applications make use of induction linac driven beams having nominal pulse widths of only 40 ns; however, the relatively low peak E-fields associated with these TW structures (as discussed in a later Section) imply that higher levels of peak RF power could be tolerated, or substantially longer pulse widths could be sustained.

TW output structures can be designed with beam apertures greater than $\lambda_0/2$ and are, therefore, particularly adaptable for operation with high current, large edge emittance beams ($\beta\gamma\varepsilon$ > 1000mm-mrad) having broad cross sections ($2a/\lambda_0 \simeq 0.4$). Although large aperture designs result in a considerable loss of unit length shunt impedance, increasing the circuit length to compensate for this loss provides an added benefit because the beam induced fields can then be established over an extended distance substantially reducing the circuit maximum E-field.

When maximum power extraction is desired, the multicell TW structure can be designed to maintain near-optimum interaction conditions over the full length of the circuit by tapering the phase velocity to control de-bunching forces and maintain synchronism as the charge centroid is continuously de-accelerated. (Although this interaction is the inverse of that which occurs in externally driven high field gradient, high current TW buncher structures,[3] the same analytical design procedure can be applied.) Yet another technique for maintaining the RF current amplitude during traversal of the output structure is the use of a TW circuit and solenoid combination designed to allow the beam diameter to expand appreciably during growth of the circuit field gradient and extraction of RF power. (Refer to the TW klystron X-791 discussion in a following Section.)

Offsetting the advantages of TW output structures for high current applications is the risk of encountering pulse shortening and other beam induced high order mode instabilities caused by extending the circuit interaction length or by using multiple circuit arrays.

Choppertron TW Output Structures

The choppertron is a TW RF generator designed to operate with a 3MeV 1000A induction linac in support of the TBA[4] and Relativistic Klystron High Gradient Accelerator test programs at LLNL.[5] This RF generator comprises a 5.7 GHz chopper driver stage immersed in an axial magnetic field, and an 11.4 GHz TW dual output stage with each TW circuit designed to extract 250 MW of power at an RF current of approximately 450A. The principle of operation, design philosophy, and fabrication of the RF generator have been presented elsewhere,[1] and only the TW output structure characteristics will be discussed in this paper.

Each TW output structure has an overall length of $2\lambda_0$ and comprises five (three SST and two copper) velocity of light cells and a sidewall coupled, offset output cavity connected to a tapered WR90 RWG output arm via a special RF/vacuum flange designed as an integral part of the output cavity body. This configuration allowed short radial RWG feeds to be run directly from the centerline through the narrow spaces between the solenoid windings, instead of along the inside of the solenoid. Thus the solenoid bobbin diameters, as well as the size, weight and dissipation of the solenoid windings were significantly reduced.

Figure 1 shows views of the dual output structures, including the WR90 RWG and water-cooling connections, during installation of the solenoid modules.

A circuit beam aperture of 14 mm was chosen for this 11.4 GHz application as a design compromise between accommodating the relatively high beam emittance, and limiting the length of the structure without exceeding a maximum surface E-field design goal of 1600 kV/cm. This short pulse operation design goal was consistent with not exceeding an average E-field of 500 kV/cm in the output cavity.

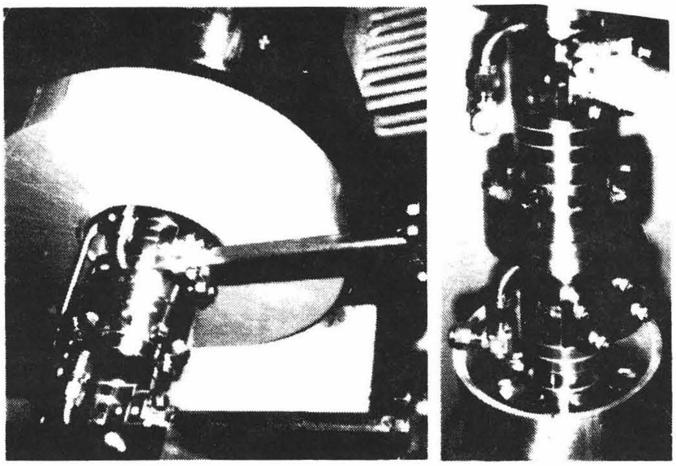


Figure 1. Dual TW Output Structures Shown during Assembly of the Choppertron.

The middle graph in Figure 2 shows the buildup of maximum surface E-field with distance along a choppertron TW output structure for a peak RF output power of 250 MW.

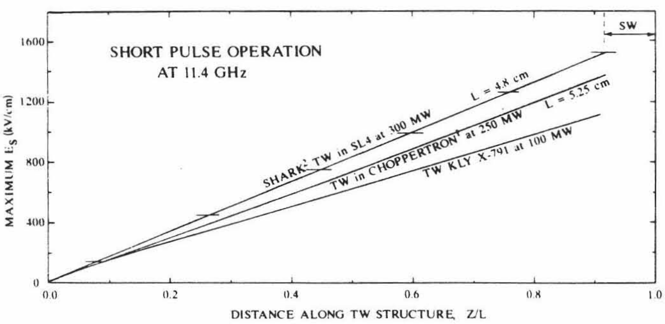


Figure 2. Maximum Surface E-Field Buildup in TW Output Structures.

Each choppertron output structure has an RF filling time of 1.05 ns, and a TW shunt impedance of 1.4 MΩ, giving a theoretical peak voltage reduction for synchronous on crest particles of approximately 1200 keV at an RF output power of 250 MW, with circuit total skin losses of less than 1 percent, and an output cavity average E-field of 450 kV/cm.

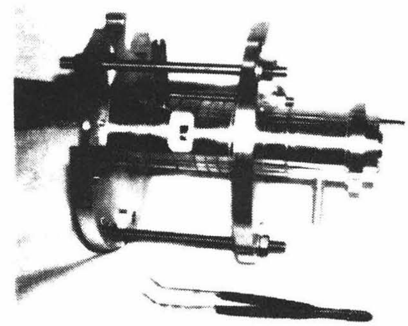
No specific precautions were taken to suppress the buildup of HOM instabilities[1] (the two prototype structures have identical frequency characteristics) so that it will be possible to evaluate this potential problem, especially in relation to the use of additional structures, during the early stages of the test program. Also, initial tests will be performed without the benefit of an HOM cut-off collimator in the drift region between the two circuits. Plans for the initial beam and RF tests are discussed in a companion paper.[5]

SL4/SHARK TW Output Structure

Since the beam energy specified for the SHARK (and SL/4) tests was considerably less than the Choppertron (refer Table I) and because of a desire for maximum power extraction, the SHARK TW structure was designed as a tapered phase velocity circuit comprising two stainless steel and four copper, $2\pi/3$ mode, cavities including a side wall coupled, offset output cavity. The circuit phase velocity was tapered from 0.94c to 0.90c over a 4.8 cm length; and the 1.01 ns RF filling time resulted in an extremely phase stable structure, insensitive to normal temperature and frequency variations, e.g., $\partial\phi/\partial f$ = 3.6 deg/10MHz and $\partial\phi/\partial T$ = 0.7 deg/10°C. This structure has a TW shunt impedance of 1.2 MΩ and was designed for an output cavity average E-field of 400 kV/cm at an output power of 250 MW. The SHARK TW circuit maximum surface E-field distribution is shown in Figure 2 for operation at a peak RF output power of 300 MW.

Figure 3 is a view of the SHARK output circuit assembly showing the bulkhead supports, water connections and RF output coupler, after final tuning and prior to attaching the WR90 output waveguide.

Figure 3. 11.4 GHz, 300 MW Tapered Phase Velocity Output Structure. Beam Aperture = 14 mmϕ



X-791 100 MW TW Klystron

This 11.4 GHz prototype RF generator was constructed as a five-section, high vacuum demountable assembly with the microwave cavities, RWG feeds, water-cooling connections, flanges and centering fixtures specially configured to allow the tube to be installed in a beam confining axial magnetic field system having a bobbin ID of only 4". The operating parameters are listed in Table II and an overall view of the tube is shown in Figure 4.

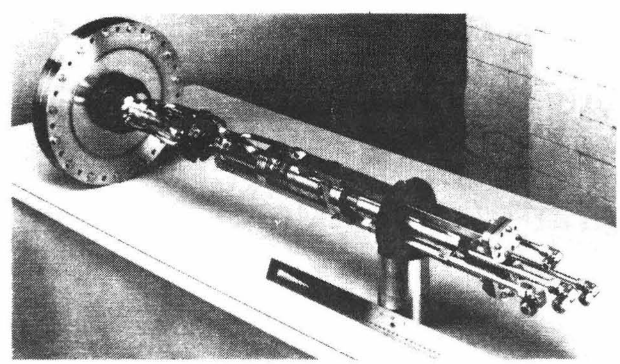


Figure 4. X-791 100MW TW Klystron with Independently Accessible Water Flow Paths for All Five Demountable Sections (Anode, Compression, Gain, Bunching and RF Extraction, and Collector).

Operating with a relatively high centerline pressure of $\approx 5\times10^{-7}$ Torr, the X-791 tube was run up to the 100 MW output power level without any evidence of RF arcing, pulse shortening, or cavity loading due to photoelectric, field, or secondary emission. (An RF output waveform is shown in Figure 8.) Key elements in the troublefree RF performance of the tube were conservative microwave circuit designs, progressively increasing beam apertures, an efficient TW output structure, and a well-matched, precision aligned, high quality axial magnetic field system.

TABLE II. X791 TW KLYSTRON OPERATING PARAMETERS

Beam Energy.	500 kV
Electron Source Operational Microperveance	≈1.3
Normalized RMS Emittance	150π mm-mrad
RF Pulse Length (FWHM)	50 ns
Pressure at Anode Centerline	$\approx 5\times10^{-7}$ Torr
Nominal Beam Diameter in Gain Section .	8-9 mm
Nominal Beam Diameter in TW Section. .	11-12 mm
Frequency.	11.4 GHz
Gain	50 dB
Peak RF Output Power (full spectrum) .	100 MW
Output Cavity Average Electric Field at 100 MW.	230 kV/cm
Filling Time of TW Output Circuit. .	1.06 ns
Klystron Overall Length.	48 in
Solenoid Bobbin ID	4.0 in
Solenoid Axial Magnetic Field. . . .	6 kG(max)
Solenoid Dissipation, less than. . .	20 kW

Figure 5 shows final brazed assemblies of the tunable gain section, the tunable buncher and TW power extraction section, and the beam collector; and the 6" rule lying at right angles across the top of the TW output structure reveals the very compact nature of these high power components. With ongoing X-band interest in longer pulse widths and RF power levels >100MW,[6] the X-791 TW output circuit was designed as a very low impedance, tapered velocity structure with an output coupler average E-field of only 230 kV/cm at a peak RF output power of 100 MW. The associated maximum surface E-field distribution is shown in Figure 2. Precautions were taken to avoid pulse shortening caused by the forward propagating[1] (and then reflecting) HEM_{11}-like modes having resonances over an 800 MHz pass band centered at 13.5 GHz.

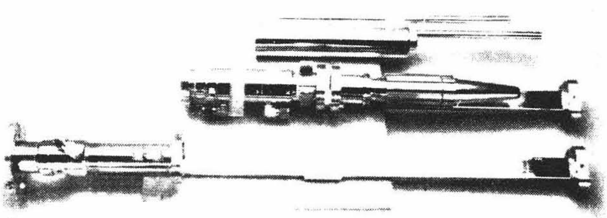


Figure 5. The Gain, TW Output and Beam Collector Sections of the X-791 Klystron.

A high electrostatic compression technique similar to that described by Lee,[7] was used for the electron source, followed by additional, near adiabatic, magnetic compression. To optimize output power, the axial magnetic field was graded along the TW output structure from 4.5 to 3 kG (as indicated in Figure 6) to give a 2:1 increase in beam cross-sectional area under saturated drive conditions.

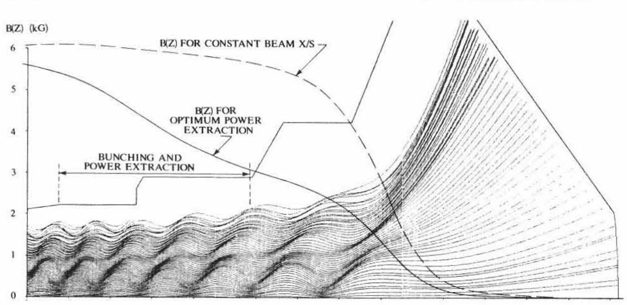


Figure 6. EGUN simulation of DC Beam with Graded Reduction of Axial Magnetic Field over the Output Structure.

Features of the X-791 beam confining magnetic field system include a 4" ID main solenoid having a dissipation of 16kW for 100MW RF operation; pancake winding transitions and a stacking technique to give full cancellation of internal axial current vectors; concentricity and collinearity of the klystron body and magnet assembly to 1/4 mm accuracy over the length of the tube; a large diameter, shaped iron, shielded bucking lens; and a precision alignment fixture that enables both the bucking lens and the main solenoid to be independently positioned axially with respect to the electron source. A view of the magnet system is shown in Figure 7.

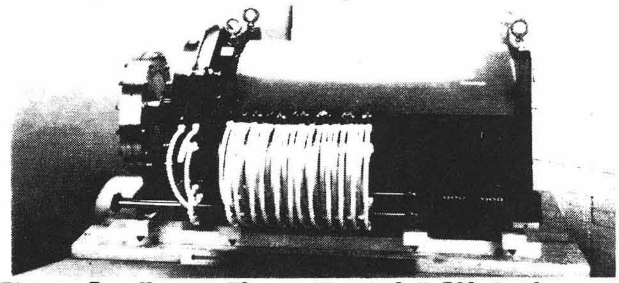
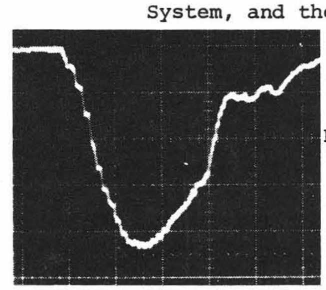


Figure 7. Vacuum Flange Mounted X-791 Anode, Independently Movable Large Bucking Lens System, and the Main Solenoid Assembly.



Beam Voltage = 500 kV
Frequency = 11.4 GHz
Peak RF Power = 100 MW
Gain = 50 dB
Diode Signal = 20 mV/div
Time Base = 20 ns/div

Figure 8. RF Output Waveform of X-791 TW Klystron Driven by an Induction Linac Beam. (The authors wish to thank the SRL/MIT Plasma Lab staff for providing this test data.)

The essential design features incorporated in the compact microwave structures discussed above, as well as the assembly, brazing and tuning procedures, and the offset coupler geometry and special RF packaging techniques, were derived from X-band TW resonant ring linac technology[8] developed over the past decade for well-logging applications.

References

1. J. Haimson and B. Mecklenburg, "Design and Construction of a Chopper Driven 11.4 GHz Traveling Wave RF Generator," 1989 PAC IEEE Conf. 89CH2669-0, p. 243.
2. M.A. Allen, et al., "High Gradient Electron Accelerator Powered by a Relativistic Klystron," Phys. Rev. Lett., 63, p. 2472, 1989.
3. J. Haimson, "Electron Bunching in Traveling Wave Linear Accelerators," Nucl. Instr. and Meth. 39 p. 13, 1966.
4. A.M. Sessler and S.S. Yu, "Relativistic Klystron Two-Beam Accelerator," Phys. Rev. Lett. 58, p. 2439, 1987.
5. G.A. Westenskow, et al., "Relativistic Klystrons for High Gradient Accelerators," Proc. Linear Accelerator Conference, Albuquerque, 1990.
6. "Electron Accelerator Techniques," Proceedings of the 6th Conf. on Electron Scattering, NIKHEF, Amsterdam, November 1989.
7. T.G. Lee, International Workshop on Next Generation Linear Colliders, SLAC, December 1988.
8. US Patent No. 4,713,581.