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200 kW, 350 – 700 MHz RF SOURCES USING MULTIPLE BEAM TRIODES

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Abstract

Calabazas Creek Research, Inc. and Communications & Power Industries, LLC are developing multiple beam triodes to produce more than 200 kW of RF power at extremely low cost and efficiencies exceeding 80%. RF power is achieved by installing the triode inside coaxial input and output cavities at the desired frequency. The multiple beam triodes developed in this program will provide RF power from 350 MHz to 700 MHz using the appropriate, tuned, resonant cavities.

This program is using eight grid-cathode assemblies to achieve 200 kW with a target efficiency exceeding 80%. A 350 MHz RF source would be approximately 36 inches high, 18 inches in diameter and weigh approximately 150 pounds. This is significantly smaller than any other RF source at this frequency and power level.

The gain is limited to approximately 14 dB, so a single beam triode-based source will serve as a driver. The combined cost and efficiency will still exceed the performance of other comparable RF sources, including solid state sources. Design issues, include grid cooling, uniformity of RF electric fields on the grids, and efficiency, will be discussed.

TRIODE RF SOURCE BASICS

The triode provides an electron beam source when driven by appropriate RF fields. The device uses a grid driven by an axial electric field to generate a pulsed electron stream at the desired RF frequency. Power from this stream is transferred to RF fields using an output cavity resonant at the pulsed frequency of the electron stream.

Figure 1 provides the basic geometry, exemplifying the simplicity of these devices. RF drive power from the input cavity enters the triode through a ceramic insulator and creates an axial electric field between the cathode and control grid. The electron beam is emitted during the positive portion of the RF cycle. Consequently, the efficiency of these sources is approximately 90%.

The pulsed electron stream excites RF fields in the output cavity at the pulse frequency, and electron beam power is transferred to these fields. This power is extracted through a capacitive or inductive coupler to the external transmission line. Tuners allow frequency control of both the input and output cavities. The spent beam power is deposited on the collector (anode) and dissipated with air or liquid cooling, depending on the average power.

A single triode can drive a multiplicity of RF sources. The triode provides its own vacuum envelope and can be plugged into appropriate cavities for the frequency desired.

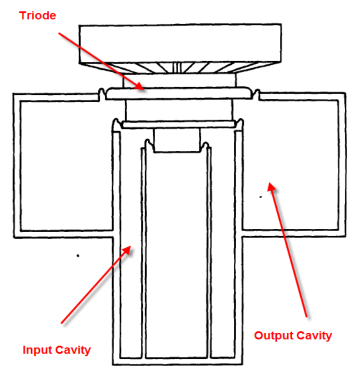

Figure 1: Schematic configuration of triode-base RF source.

MULTIPLE BEAM TRIODE

Single beam triodes were developed more than fifty years ago and are still in production. The device primarily consists of a cathode and one or more grids surrounded by a vacuum envelope. Figure 2 shows the YU-176 triode, which operates from 300 MHz to 1. 2 GHz and provides sufficient beam power to generate 25 kW of RF power.

The YU-176 grid-cathode assembly is shown in Fig. 3. The cathode consists of a flat, nickel surface coated with barium oxide. The grid is cut from commercially available tungsten screen and brazed to tungsten supports. A vacuum ceramic isolates the grid from the cathode. The assembly costs less than $1,500 in production quantities.

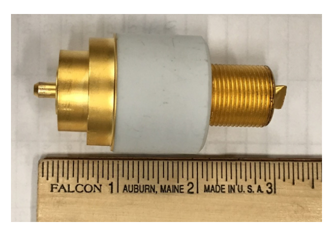

Figure 2. YU-176 triode produced by Communications & Power Industries, LLC.

This program is using eight YU-176 grid-cathode assemblies to increase the available beam power to 250 kW. Figure 4 shows the eight beam array, and Fig. 5 shows the size and configuration of complete devices, including their integral vacuum envelopes and insulating ceramics.

RF power is produced by installing the triode into a set of input and output cavities. Each is typically a single, coaxial resonator with integral tuners and couplers. Figure 6 shows solid models for a 350 MHz and 600 MHz RF source using the water-cooled (CW) multiple beam triode. Note that the sizes are dramatically smaller than comparable klystron, inductive output tube, or solid-state sources.

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Figure 3: Grid-cathode assembly for YU-176 triode.

Figure 4: Eight grid-cathode array for multiple beam triode.

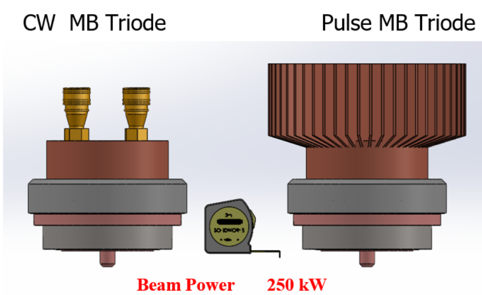

Figure 5: Solid models of water and air-cooled multiple beam triodes to produce 200 kW of RF power.

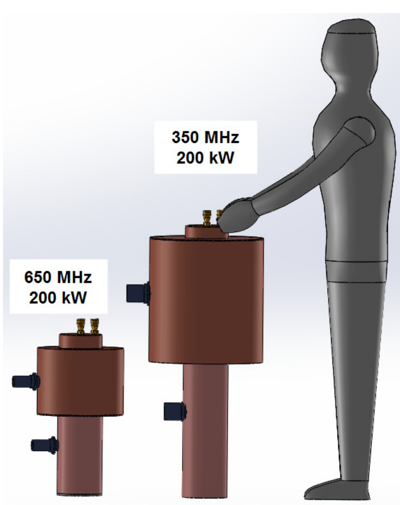

Figure 6: Solid models of 350 MHz and 600 MHz RF sources using the water-cooled, multiple beam triode of Fig. 5.

While triode-based sources are high efficiency (90%) and can produce hundreds of kilowatts of RF power, the gain is limited to approximately 14 dB. Consequently, the program is developing single beam triode sources to drive the multiple beam tubes. Even so, the total cost is almost an order of magnitude less than comparable sources.

RF SOURCE DESIGN

The RF source input cavity is required to provide uniform electric fields across all grids of the triode at the same amplitude and phase. Figure 7 shows the geometry of the multiple beam grid-cathode region with the RF drive signal path shown by the green arrows. Note that the RF drive enters along the outer periphery of the multiple beam array. CCR used HFSS to analyse the uniformity of the RF fields across the grids resulting from this asymmetrical configuration. The results shown in Fig. 8 indicate the field variation is approximately 0.6%, well within the acceptable value.

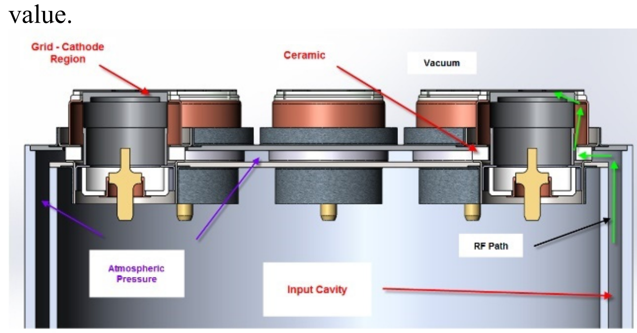

Figure 7: Grid-cathode region of multiple beam triode showing path of RF drive signal.

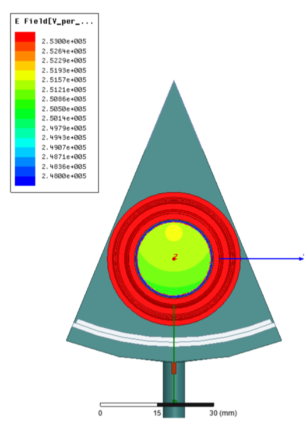

Figure 8. Electric field variation across multiple beam triode grid.

Design of the cavities is extremely simple using a process developed by Buzz Miklos more than fifty years ago [1]. The cavity parameters depend on the geometry and capacitance of the triode and the desired frequency. Once the triode is built and the capacitances measured, cavity parameters can be determined in seconds using formulas in an Excel spreadsheet.

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PROGRAM SCHEDULE

The Phase II development program began in August 2019 and is scheduled for completion in two years. The multiple beam triode for pulsed operation will be designed and built during the remainder of 2019. The 350 MHz cavity design will proceed in parallel with scheduled completion in February 2020. Before high power testing can begin, the power supply and test facilities must be upgraded. This is also scheduled for completion in February 2020, with testing of the 350 MHz source to be completed in early spring. Because of the low gain of these devices, the team will develop both the 200 kW multiple beam device and a single beam device to serve as a driver. Each single beam device will provide sufficient power to drive four 200 kW tubes. Even though it will require two triode-based sources to achieve full power, the cost is still a fraction of that for other devices. 700 MHz, 200 kW, pulsed cavities will be designed with testing scheduled for late spring and early summer.

The CW multiple beam triode development will begin in January 2020 and completed by late summer 2020. A CW version of the 350 MHz source will be designed, beginning in late spring 2020 with scheduled completion in fall 2020. Testing is scheduled for completion in early 2021. If resources are available, a 200 kW CW, 700 MHz, RF source will be designed, built and tested in spring 2021.

COST COMPARISON

The simplicity of triode-based sources results in dramatically lower costs for 200 kW sources in the 350 – 700 MHz range over other options A comparable klystron would be significantly larger and cost approximately $800K. Pulsed, multiple beam inductive output tubes are being developed in this frequency range with cost estimates around $1M. A comparable solid-state source would require approximately 250 square feet of floor space and cost approximately $800K [2].

In contrast, a 200 kW, multiple beam triode, RF source is estimated to cost approximately $55K. A 25 kW driver should cost approximately $45K, for a total estimated cost of $100K. This information, along with efficiency values, are summarized in Fig. 9.

Product	**Price**		**Efficiency**
Klystron:	$800K	($4/W)	50-60%
MBIOT:	$400-800K	($2-$4/W)	65-70%
Solid State:	>$750K	($4/W)	~50%
Triode-based RF Source			
25 kW Driver		$45K	~ 90%
200 KW MB source		$55K	~ 90%
Total		$100K	~ 80%
Triode-base source cost :		$0.50/Watt	

Figure 9. Cost for 200 kW CW, 350 MHz RF sources.

CONCLUSION

Extremely low cost, high efficiency RF sources are under development to provide power from 350 to 700 MHz. The devices will operate with efficiencies exceeding 80% and will be extremely compact. Both pulsed and CW RF sources will be built and tested. The first pulsed sources should complete testing by summer 2020 with CW sources built and tested by early 2021.

ACKNOWLEDGMENTS

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[2] P. Marchand, R. L. Lopes, J. Polian, F. Ribeiro, and T. Ruan, "High Power (35 KW and 190 KW) 352 MHZ Solid State Amplifiers for Synchrotron SOLEIL", in *Proc. 9th European Particle Accelerator Conf. (EPAC'04)*, Lucerne, Switzerland, Jul. 2004, paper THPKF031.