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HIGH EFFICIENCY, LOW COST RF SOURCES FOR ACCELERATORS AND COLLIDERS*

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Abstract

Calabazas Creek Research, Inc. (CCR) is collaborating with a number of institutions to develop new RF sources for accelerators and colliders. An overriding focus is on reducing acquisition cost as well as the continuing cost by increasing efficiency. Consequently, the goal of these programs is efficiencies exceeding 80% at power levels above 100 kW CW. Two research efforts involve modifying or controlling magnetrons to allow fast control of the frequency, amplitude and phase for beam loading compensation. Two techniques are described. Research is also investigating two multiple beam sources that achieve high efficiency through Class C operation. A 350 MHz RF source, nearing completion, uses power grid tubes, and a 700 GHz source will use an inductive output tube. An L-Band klystron is also nearing completion and is designed to produce 100 kW at 80% efficiency. These programs will be briefly described.

100 KW MAGNETRON SYSTEM

Figure 1 shows a photograph of the magnetron system designed to deliver RF power with output power and phase control by an active feedback circuit compensating for beam loading. The system was designed for high Q, superconducting cavities. The system uses an approach developed by Fermilab in which power is controlled by modulating the phase of an RF locking signal directed into the magnetron output [1]. By modulating the phase of the locking signal one can shift power into sidebands. Power in these sidebands is reflected from high Q cavities, thereby reducing power into the cavity. Principal components include the magnetron, a four-port circulator, an RF driver, and control circuitry. These are integrated into the system shown in Fig. 1, including water cooling, interlocks, diagnostic instruments, and power supply for the driver. The high-power supply for the magnetron in not included in this package. Figure 2 shows the relative amplitude at the fundamental frequency as a function of phase modulation. Power in side bands is reflected and absorbed in the circulator.

The system was tested to full peak power at Fermilab, where the data in Fig. 2 was obtained. The system efficiency exceeded 80% for all modes of operation. The system shown in Fig. 2 used a 5 kW klystron as the driver, but only 316 W was required. This power is readily available from solid state sources.

Estimated cost for the system as shown is approximately $100K, which is $1/Watt. This is approximately 25% of the cost for a comparable klystron or solid-state source at this frequency and power level.

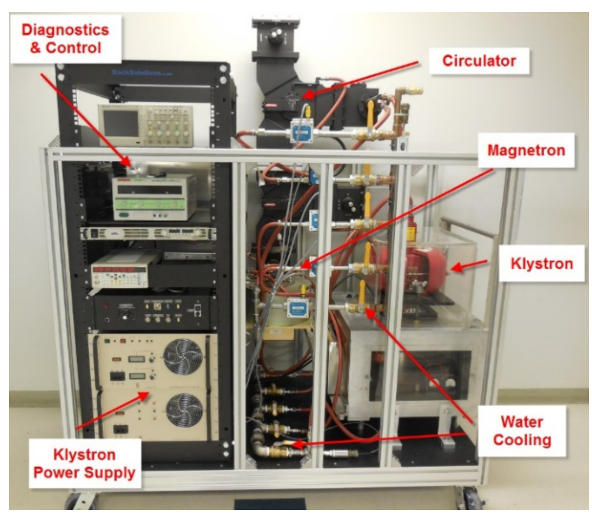

Figure 1: 1.3 GHz, 100 KW, Magnetron System with fast phase and amplitude control.

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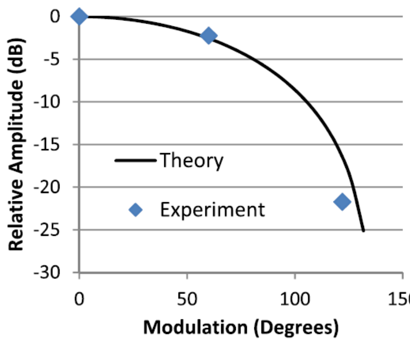

Figure 2: Power at fundamental frequency as function of driver phase modulation.

COMPACT MAGNETRON WITH FAST FREQUENCY AND PHASE CONTROL

CCR is teamed with SLAC National Accelerator Laboratory (SLAC) and Communications & Power Industries LLC to develop a compact magnetron RF source with fast phase and frequency control. This approach eliminates the circulator by using varactor diodes to modulate the capacitance, and thus the frequency, of a magnetron cavity. A 0.5 pF capacitance change shifts the magnetron frequency by 5 MHz. Figure 3 shows a MAGIC simulation of a magnetron where capacitance in controlled using a varactor. Figure 4 shows a suitable diode for this application.

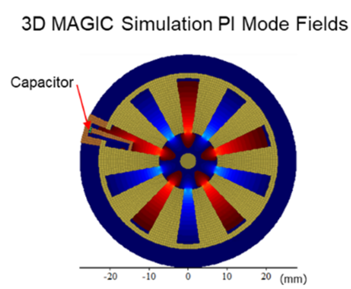

Figure 3: 3D MAGIC simulation of pi mode fields in a magnetron where varactors modulate capacitance of a cavity.

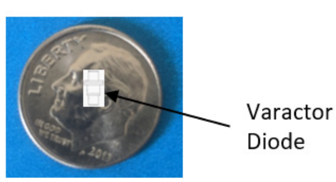

Figure 4: Microsemi GC1712 varactor diode.

This program integrates several innovative features to provide an extremely compact, low-cost configuration. The system can incorporate adaptive feed forward to cancel the high frequency resonances of the switching power supply. Optionally, an analog loop can be used for fast, high bandwidth control.

The Navy is funding development of as S-Band, 5 kW prototype system for a communications application. CCR and SLAC are pursuing a higher power version for accelerator applications.

1.3 GHZ, ULTRA-HIGH EFFICIENCY KLYSTRON

Interest has increased recently in klystron due to new circuit design techniques predicting significantly higher efficiency than available in conventional klystrons. These circuit design approaches facilitate more efficient bunching of electrons prior to power extraction in the output cavity. CCR and Leidos are using the Core Oscillation Method (COM) to achieve more than 80% efficiency in a 1.3 GHz, 100 kW klystron. Figure 5 shows a model of the klystron, which is currently being assembled. The COM approach achieves more efficient bunching by providing increased length. The circuit length for the klystron being built is 220 cm. This increases the tube length but uses fewer cavities than other approaches, such as the Bunch, Align, and Collect (BAC) method.

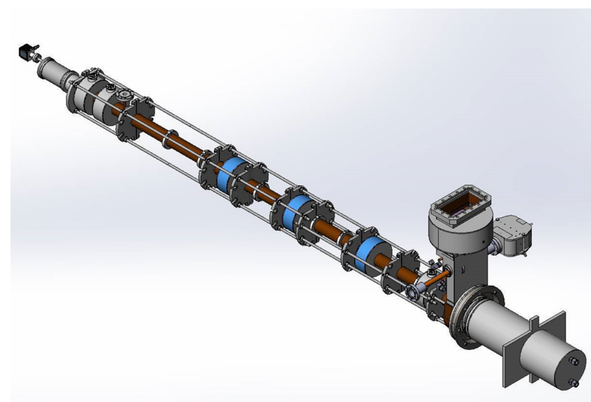

Figure 5: Solid model of 1.3 GHz klystron designed to produce 100 kW at more than 80% efficiency.

The solenoid was received, and the cavities are currently being cold tested. Other major subassemblies, including the gun, collector, and output window are complete, and the test set is currently being reconfigured to accommodate the increased length. High power tests are scheduled for summer 2021.

MULTIPLE BEAM POWER GRID TUBES

Power grid tubes have been in use for more than fifty years and have produced RF power at efficiencies approaching, and sometimes exceeding 90%. These tubes provide beam power for sources producing tens of kilowatts and frequencies from 300 MHz to 1 GHz. The high efficiency results from Class C operation, where the pulsed electron beam is generated by RF modulation of a grid. Gain is typically 14 dB.

This program is developing multiple beam grid tubes to provide sufficient beam power to produce 200 kW or more of RF power. Figure 6 shows the array of eight grid-cathode assemblies powering the prototype tube. These assemblies use flat cathodes and grids cut from commercial tungsten screen. Consequently, the cost is extremely low

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compared to other vacuum electron devices. This array is integrated with an anode/collector into a vacuum device, shown in Fig. 7.

Figure 6: Array of eight grid-cathode assemblies to produce 230 kW of beam power.

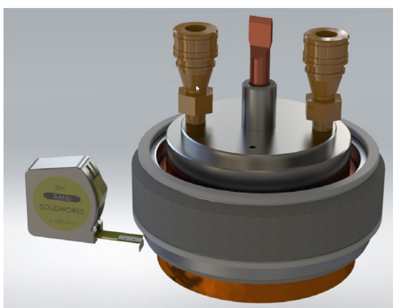

Figure 7: Solid model of the 200 kW, multiple beam power grid tube.

RF power is generated when the tube is integrated with external input and output cavities. The frequency is determined by the cavity geometry. The tube can operate from 300 MHz to more than 1 GHz. Cavity tuners allow a single device to operate over a 150 MHz frequency range.

Because of the inherently low gain, CCR is also developing a single beam power grid tube and cavities to drive the multiple beam device. Consequently, a complete system consists of two tubes, as shown in Fig. 8. The total gain will be approximately 28 dB with an efficiency of approximately 75%. Even though two tubes are required, the cost is surprisingly low. The total cost for the single beam driver and multiple beam output tube would be approximately $0.50/Watt, or about 1/8 the cost of a klystron or solid state source. No magnetic field is required, and the tube operates at less than 10 kV. Prototype tubes are currently being assembled, and testing is scheduled for summer 2021.

MULTIPLE BEAM INDUCTIVE OUTPUT TUBE

Like power grid tubes, IOTs operate in Class C and typically operate with efficiencies exceeding 75%. CCR is teamed with Georgia Tech Research Institute and Communications & Power Industries, LLC to develop multiple beam IOTs operating at more than 80% efficiency. The program is also developing molybdenum grids and an improved input coupler to reduce cost and increase yield. The prototype device will be designed to produce 200 kW CW at 700 MHz.

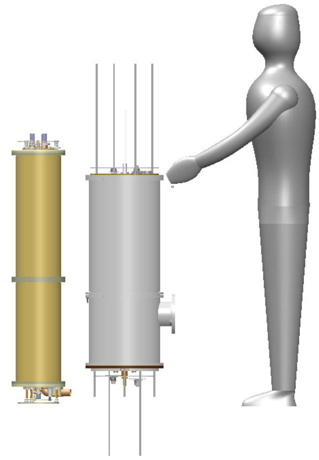

Figure 8: 350 MHz, 200 kW RF system source.

CCR is exploring addition of 3rd harmonic to the drive power to improve electron bunching at the output cavity. Simulations predict that addition of 3rd harmonic at the appropriate power and phase can increase efficiency 7-10%.

IOTs traditionally use pyrolytic graphite (PG) grids to handle the power loading. Interestingly, the power loading is dominated by radiative heating from the cathode rather than electron beam loading. Molebdenum grids, in contrast, are primarily heated by the pulsed electron beam, and simulations indicate they will be considerably cooler. This could reduce issues of spurious grid emission.

The program is also developing a much simpler input coupler than currently used for multiple beam IOTs. This will dramatically reduce cost and risk. The primary challenge is developing a coupler that can transmit both fundamental and 3rd harmonic power. Figure 9 shows an HFSS simulation of the input coupler. The device is currently being designed, and the prototype device is scheduled for test in spring 2022.

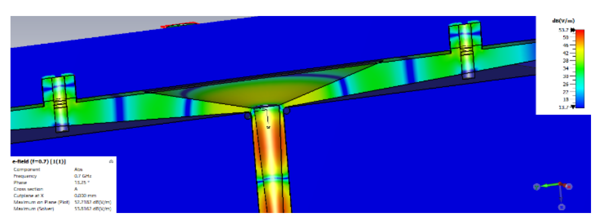

Figure 9: High Frequency Structure Simulation of input coupler for multiple beam IOT.

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