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A 100 kW 1.3 GHz MAGNETRON SYSTEM WITH AMPLITUDE AND PHASE CONTROL

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Abstract

Calabazas Creek Research, Inc., Fermilab, and Communications & Power Industries, LLC, developed a 100 kW peak, 10 kW average, 1.3 GHz, magnetron-based, RF system for driving accelerators. Efficiency varied between 81% and 87%. Phase locking uses a novel approach that provides fast amplitude and phase control when coupled into a superconducting accelerator cavity [1]. The system was successfully tested at Fermilab and produced 100 kW in 1.5 ms pulses at a repetition rate of 2 pps. A locking bandwidth of 0.9 MHz was achieved with a drive signal of 269 W injected through a 4 port circulator. The phase locking signal was 25 dB below the magnetron output power. The spectrum of the phase locked magnetron was suitable for driving accelerator cavities. Phase modulation was demonstrated to 50 kHz (the limit of the available driver source). The average power was limited by available conditioning time. Scaling indicates 42 kW of average power should be achievable. Estimated cost is less than $1/Watt of delivered RF power. System design and performance measurements will be presented.

INTRODUCTION

The magnetron is a highly efficient and relatively inexpensive source of RF power. Magnetrons with efficiencies exceeding 85% are available at 915 MHz and are commonly used in industrial RF heating systems. These are free-running oscillators and are not suitable where control of the frequency and phase are critical, including many accelerator systems. While one can control the amplitude by varying the beam current, this cannot be achieved on a sufficiently fast time scale for systems requiring feedback control. Calabazas Creek Research, Inc., Fermilab and Communications and Power Industries, LLC developed a phase-locked, 1.3 GHz magnetron-based RF system with fast amplitude control for accelerator applications.

The system provides 10o kW of peak power with a 10% duty cycle. The magnetron is phase-locked using a technique developed by Fermilab [1] that employs phase modulation of the locking signal to produce sidebands that are rejected by a high Q load, such as a superconducting cavity. Power in the sidebands effectively reduces the power delivered to the cavity and provides amplitude modulation on a very fast time scale.

SYSTEM DESCRIPTION

The magnetron and its driver and ancillary equipment are enclosed in a support frame, as shown in Figure 1. The magnetron and its solenoid, shown in Fig. 2, is driven by a klystron capable of 5 kW. The high driver power was chosen to explore a wide parameter space, but, much lower power iss required for locking. A 4-port circulator was used to inject the locking signal. For these experiments, the output of the system was shorted to reflect the power from the magnetron into the circulator load.

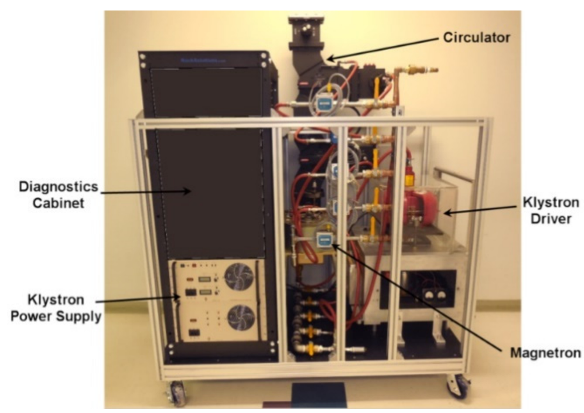

Figure 1: Photograph of magnetron system

AMPLITUDE CONTROL

While phase control has been available for many years, the approach developed by Fermilab also provides amplitude control on a fast time scale, Phase modulation of the phase locking signal shifts power into side bands. For very

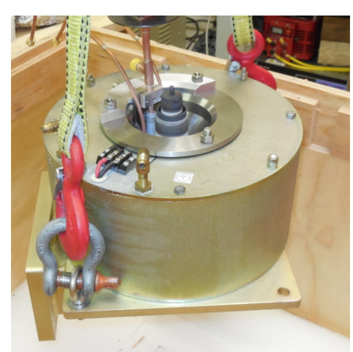

Figure 2: Photograph of magnetron inside solenoid

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high Q cavities, such as those in super conducting accelerators, this power is reflected back toward the RF source where it is absorbed in the circulator load. This effectively reduces the power delivered to the cavity.

Figure 3 shows a block diagram of the configuration tested at Fermilab. The RF locking signal from the klystron was injected into the magnetron using a 4-port circulator and the magnetron output power from the circulator was reflected by a short into the circulator's load. When used to drive an accelerator cavity, this power would be transmitted to the accelerator.

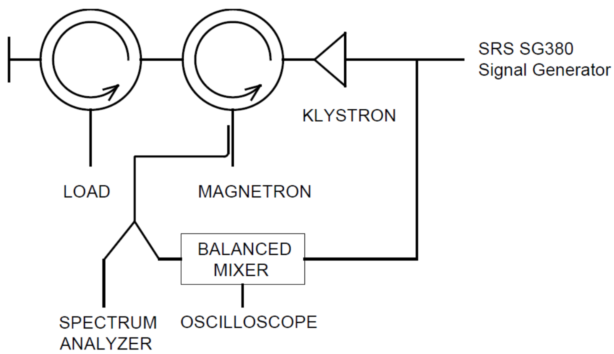

Figure 3: Block diagram of the experimental configuration

The locking bandwidth as a function of drive power is shown in Figure 4. Also shown are calculated bandwidth from Adler's equation

$$BW = \frac{f_o}{Q}\left(\frac{P_{lock}}{P_{out}}\right)^2 \tag{1}$$

where Q is the magnetron loaded quality factor, and calculations by Kurokawa [2].

The magnetron's external Q was 185. Kurokawa's formulation includes the presence of a circulator and is the same as Equation (1), but with a factor of 2 in the numerator.

TEST PERFORMANCE

Figure 5 shows the effect of phase modulating the locking signal on the magnetron output. The magnetron operated at the natural (unlocked) frequency when locked with a signal 25 dB below the output power. Phase modulation was introduced from the klystron at 50 kHz. The figure shows increased power diverted to the side bands with increasing phase modulation, thereby reducing power at the center frequency.

A plot of the observed power at the center frequency versus the modulation is shown in Figure 6. Also shown is the predicted power [3].

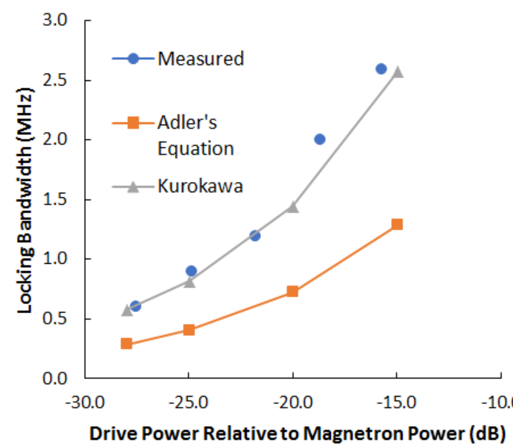

Figure 4: Locking bandwidth as a function of locking drive power as measured and predicted by Adler's and Kurokawa's equations.

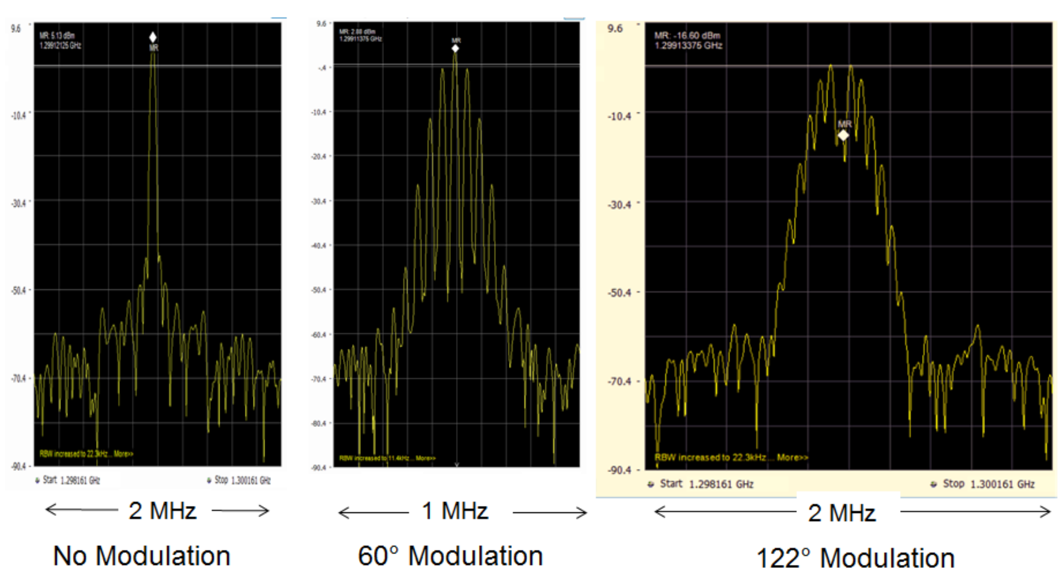

Figure 5: 50 KHz phase modulation with 269 W locking power and 66.5 kW magnetron output (-25 dB).

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ESTIMATE COST

The principal components of a commercial system include the magnetron, solid-state locking amplifier, 4-port circulator, power supplies, and control electronics. The system shown in Figure 1 included a klystron and its power supplies, which can be replaced with a solid-state amplifier. The estimated cost for the upgraded system is provided in Table 1. The estimate is for a single system, without the magnetron power supply/modulator. The modulator should cost less than that for an equivalent klystron, since the voltage will be lower. There would be a considerable cost reduction if multiple systems were purchased. For example, for 20 magnetron-based systems, the cost for each would be less than $84,000. This is less than $1/W of delivered RF power.

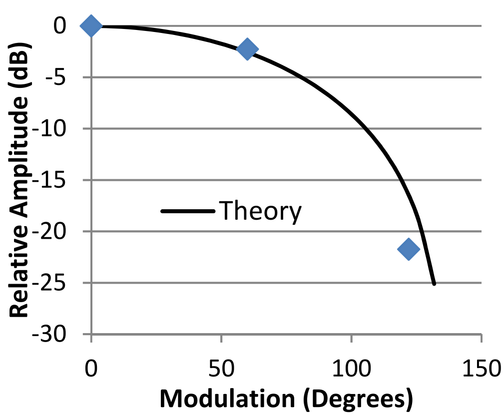

Figure 6: Relative power at center frequency as a function of modulation phase

CONCLUSION

A high efficiency, magnetron system capable of phase and amplitude control for driving high Q accelerator cavities was built and demonstrated. The system produced 100 kW at 1.3 GHz. A drive signal 25 dB below the magnetron output power provided a locking bandwidth of 0.9 MHz. Consequently, the system can be controlled with a 316 W solid state source.

The system achieved 300 W of average power, limited by the available test time. The system was scaled from a 100 kW, 915 MHz device to provide 10 kW of average power.

Table 1: Estimated Cost of a 100 kW 1300 MHz Magnetron System With Amplitude and Phase Control

Magnetron	$72,000
500 W SS amplifier for locking	$17,000
Circulator w waveguide	$20,000
Controls	$10,000
Packaging	$10,000
TOTAL	$129,000

ACKNOWLEDGMENTS

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