

## USE OF AN INJECTION LOCKED MAGNETRON TO DRIVE A SUPERCONDUCTING RF CAVITY\*

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### Abstract

The use of an injection locked CW magnetron to drive a 2.45 GHz superconducting RF cavity has been successfully demonstrated. With a locking power less than -27 dB with respect to the output and with a phase control system acting on the locking signal, cavity phase was accurately controlled for hours at a time without loss of lock while suppressing microphonics. The phase control accuracy achieved was 0.8 ° r.m.s. The main contributing disturbance limiting ultimate phase control was power supply ripple from the low specification switch mode power supply used for the experiment.

### INTRODUCTION

The application of magnetrons attracts periodic attention in the chase for high efficiency and low cost RF power for large scale accelerator systems [1 - 3]. The successful experiment presented here, we believe, is the first ever demonstration that the accelerating phase of a high Q superconducting cavity can be accurately controlled when driven by an injection locked magnetron. Moreover the locking power relative to the output power was -27 dB which is less than the drive power one would have needed for an IOT amplifier.

### CAVITY AND MAGNETRON

The experiment was conducted with a single-cell superconducting cavity with its acceleration mode at 2.45 GHz and  $Q_0(2K) = 5.22 \times 10^9$ . The cavity is shown in Figure 1. The cavity had simple coaxial input and output couplers at each end and the tests were conducted in a vertical cryostat (VTA) at 2 K. The input coupler was adjusted to give an external Q of  $2.6 \times 10^6$  as would be typical for an application with some beam loading.



Figure 1: 2.45 GHz niobium cavity for the cold (2K) test.

The output coupler was adjusted to have an external Q of  $2.2 \times 10^{10}$ . The magnetron used was a Panasonic

2M137, 1.2 kW, 12-vane “cooker” type. Experimental results presented here were taken for a magnetron output power of 530 W. Forward power to the cavity was reduced to 2.4 W for operational reasons. The gradient in the cavity was 0.93 MV/m. The magnetron was also operated with a reduced heater power to ensure its operation was in a low noise region [4]. Controlled levels of microphonics could be introduced to the top of Dewar.

### LLRF SYSTEM

A key aspect of the experiment was to show that the phase of a superconducting cavity could be accurately controlled by manipulation of the phase of the locking signal. The LLRF system and high power RF circuit utilized is shown in Figure 2. The DC cathode voltage for the magnetron was supplied from a modified commercial switched mode power supply so that the pulse width modulator could be controlled externally. For industrial applications the pulse width modulator is operated in a constant current control loop. With external control one has many options including a fixed modulation or operation at constant frequency utilizing the magnetron’s pushing curve. Constant natural frequency control without a superconducting cavity has been described previously [4-6]. For the tests described here, ultimate cavity phase control utilizing the Agilent E4428 source and constant pulse width modulation out performed cavity phase control with a magnetron constant natural frequency loop. It was not possible to integrate the Agilent source with our PLL loop for a constant magnetron frequency operation; the low cost embedded oscillators in our PLL brought down overall system performance by very low frequency offsets with respect to the Agilent source.

In Figure 2 the low pass filter after the switched mode power supply reduces 42 kHz ripple from the chopper. The magnetron heater has an AC supply which is not ideal as it adds voltage ripple to the high voltage and hence phase ripple as determined by the magnetron pushing characteristic. The heater power needed for accurate locking is typically in the range of 15% to 30% of power required for start up.

The magnetron is operated as a reflection amplifier [7]. The source signal from the Agilent E4428 is split three ways. One signal goes as a reference to a double balanced mixer on the cavity output coupler to make high resolution phase measurements. The second signal is taken as a reference for the phase control loop. The third signal drives the injection; the phase of this signal is adjusted by the IQ modulator of the cavity phase control loop and is then injected into the cavity via three

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circulators. The circulator 3 separates the magnetron output from the injected input. The circulator 2 diverts reflected power from the cavity away from the injection source to a load. As the high power circulators have isolation as little as -20dB, an additional low power circulator 1 is used to protect the 1 W amplifier.

The stub tuner 1 allows the output power and frequency of the magnetron to be adjusted with some independence to the anode current. Adjusting anode current and magnetron reflected power simultaneously allows the

magnetron output power to be tuned without changing its natural frequency. The magnetron needs to operate at its natural frequency to minimize locking power is determined by the Adler equation [8].

Initially the magnetron is energized at a high heater power; it is then reduced after the start up. Without a magnetron natural frequency control loop, once the temperature of the anode has stabilized, the anode current is adjusted manually until the magnetron's natural frequency is almost the same as that of the locking signal

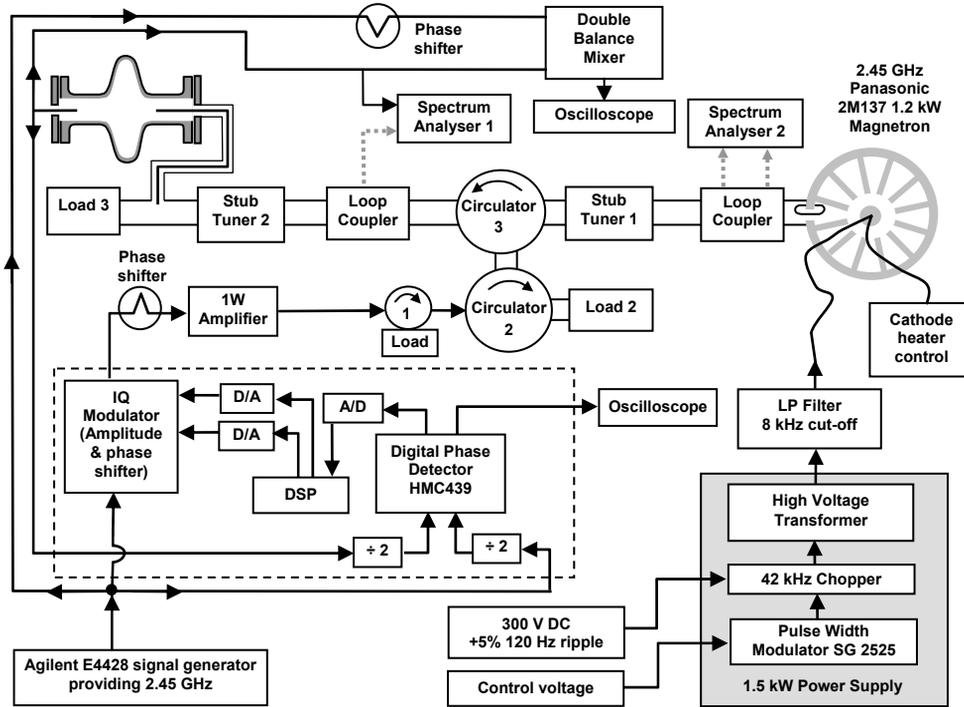


Figure 2: Low and high levels RF control layout of the magnetron phase lock to a SRF cavity.

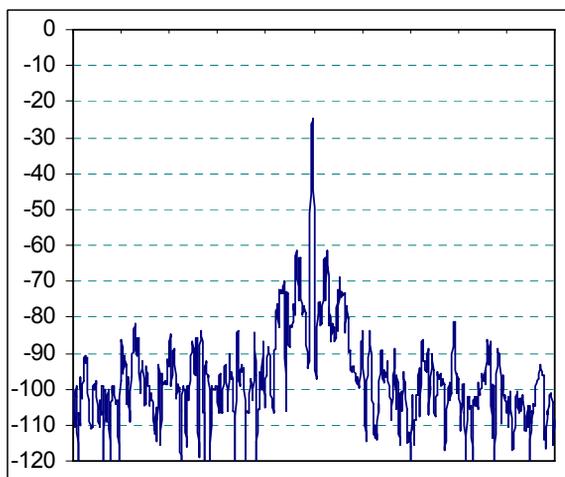


Figure 3: Spectral output (dB) from cavity with injection signal only (1 kHz bandwidth, 3 Hz resolution bandwidth).

At this instant the magnetron locks and behaves as a constant output amplifier, i.e. the phase of the output

follows the phase of the input. The LLRF control system used in Figure 2 is a generic system for a wide range of frequencies [9]. Its ability to control amplitude and phase through IQ modulation was not used in this test. The phase was measured using a Hittite HMC439QS16G digital phase detector in conjunction with HMC437MS dividers. The benefit of this approach is its excellent phase linearity and hence any offset can be varied accurately during operation.

### EXPERIMENTAL RESULTS

Before the magnetron was energized, the locking signal routing the magnetron passive circuit was transmitted through the SRF cavity. Figure 3 shows the spectral output of the cavity without the Digital Signal Process (DSP) control. A -37 dB microphonic at +/-30 Hz band can be observed. Figure 4, left shows the same spectral output once the magnetron was energized and injection locked but without the DSP control. The resonance peak had increased by 25 dB. In addition to the microphonics we saw a very large phase jitter at the power mains

frequency and its harmonics, 60, 120 Hz etc. Application of the DSP control (shown in Figure 4, right) reduced the microphonic phase jitter by -13 dB, the 60 Hz by -20 dB and the 120 Hz by -17 dB correspondingly.

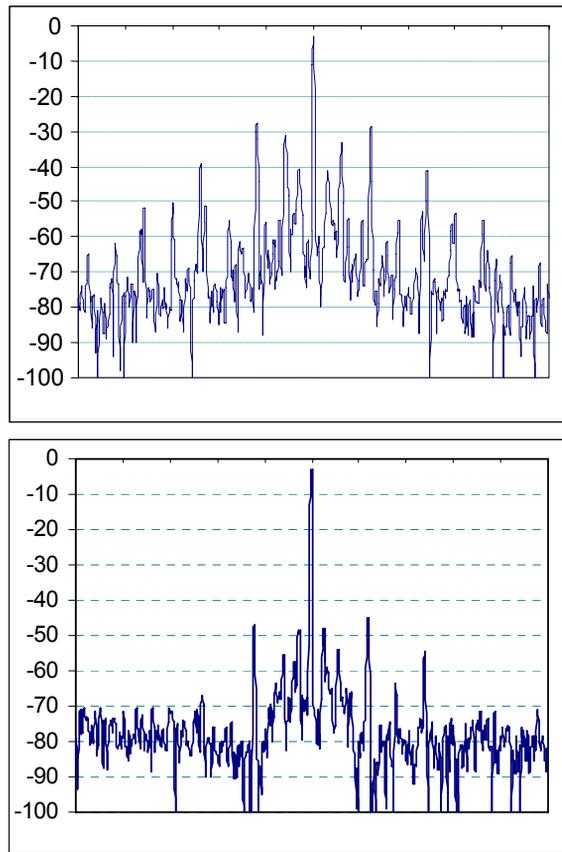


Figure 4: Spectral output (dB) from injection locked magnetron, 1 kHz bandwidth, 3 Hz resolution bandwidth. (Top) without DSP phase control, (Bottom) with DSP phase control.

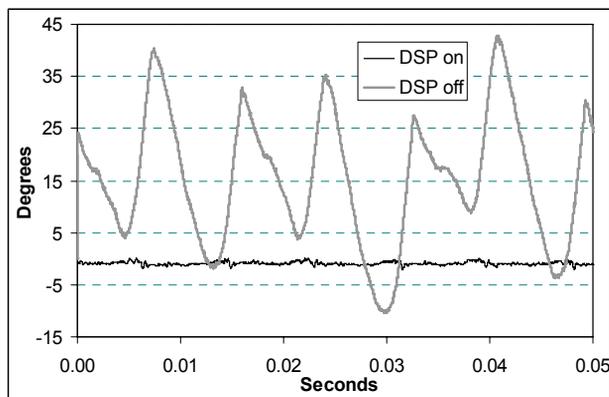


Figure 5: Phase jitter measurement from the cavity output.

Figure 5 shows the effect of programmable DSP phase control in the time domain record. The peak-to-peak phase noise of the cavity output is reduced from  $50^\circ$  with the DSP off to  $2^\circ$  ( $0.8^\circ$  r.m.s.) with the DSP on. The phase

to voltage conversion from the double balance mixer was carefully benchmarked being  $9^\circ/V$ .

## CONCLUSIONS

The phase control tolerance demonstrated in this experiment approaches that required for a range of long pulse proton driver and some CW accelerator applications. The reduction of phase noise from microphonics and power supply ripple is clearly demonstrated. Most of the residual phase noise is coming from 60 Hz components in the high voltage power supply and the cathode heater supply. The residual phase noise can be reduced further by a ripple free high voltage power supply and a DC supplied cathode heater. A good quality of VCO integrated with frequency synthesizer and less mains noise pickup in the PLL loop is desired in a better phase lock in the frequency lock mode.

For applications requiring fast amplitude and phase control, the outputs from two magnetrons could be controlled by phase modulators and combined by a magic Tee to give the desired amplitude and phase.

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