SIMULATION AND EXPERIMENTAL STUDIES OF A 2.45GHz MAGNETRON SOURCE FOR AN SRF CAVITY WITH FIELD AMPLITUDE AND PHASE CONTROLS*

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Abstract

Phase lock to an SRF cavity by using injection signal through output waveguide of a magnetron has been demonstrated [1, 3]. Amplitude control using magnetic field trimming and anode voltage modulation has been studied using MATLAB/Simulink simulations [2]. Based on these, we are planning to use an FPGA based digital Low Level RF (LLRF) system, which allows applying various types of control algorithms in order to achieve the required accelerating field stability. Since the 1497 MHz magnetron is still in the design stage, the proof of principle measurements of a commercial 2450 MHz magnetron are carried out to characterize the anode I-V curve, output power (the tube electronic efficiency), frequency dependence on the anode current (frequency pushing) and the Rieke diagram (frequency pulling by the reactive load). Based on early Simulink simulation, experimental data and extension of the Adler equation governing injection phase stability by Chen's model, the specification of the new LLRF control chassis for both 2450 and 1497MHz systems are presented in this paper.

INTRODUCTION

As a drop-in replacement for the CEBAF 13kW CW klystron system, a 1497 MHz, CW type high-efficiency magnetron using injection phase lock with amplitude variation is under development. Magnetrons used in industrial and medical accelerators normally have 85-95% electronic efficiency, much higher than typical klystrons within the same perveances [2]. Current CEBAF klystrons only have efficiency of 35-55%. The ultimate goal of using magnetrons instead of klystrons for the CEBAF and future JLEIC machines is for both capital and operation cost reduction. The capital cost of a klystron or a solid state amplifier is in the range $5-25 per output Watt depending on the power rate and production quantity. However a magnetron, which can be both operated in CW or pulse modes if it is designed and controlled properly, can be operated with both high gain and high efficiency. Its production cost can be as low as $0.1 per output Watt like a typical oven magnetron. The performance of an injection locked CW magnetron to phase control a SRF cavity was first demonstrated at JLab in conjunction with Lancaster University, UK, in 2010 [1, 3] with accuracy of 0.95° rms at -23.5dB injection signal.

To re-establish the JLab magnetron test stand and to further investigate phase and amplitude control accuracy of an SRF cavity by a dedicated digital LLRF controller, a new 2.45GHz magnetron system TMA12 including WR340 waveguide components was purchased from a company, MKS for Alter Products. It is intended to duplicate the National Electronics 2M137IL magnetron head used in 2010 [1, 3]. A 3-stub tuner to vary the magnetron output impedance and an S-Team Homer in-line impedance analyser of WR340 waveguide type were also used for the Rieke diagram measurement.

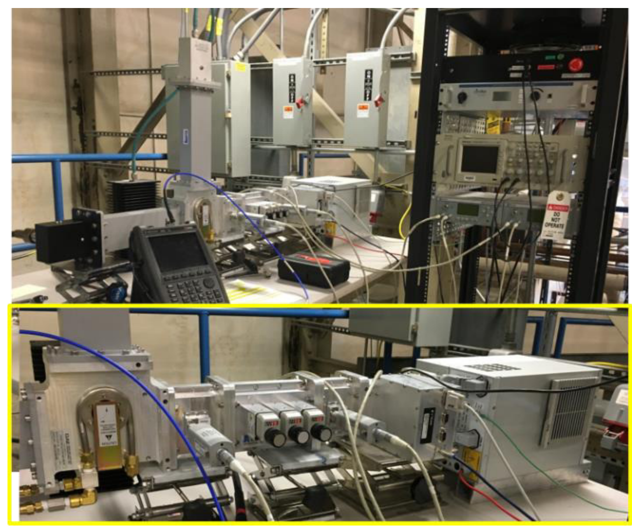

Figure 1: 2.45GHz, 1.2kW magnetron test stand (top) and the setup (bottom) connected to a matched load.

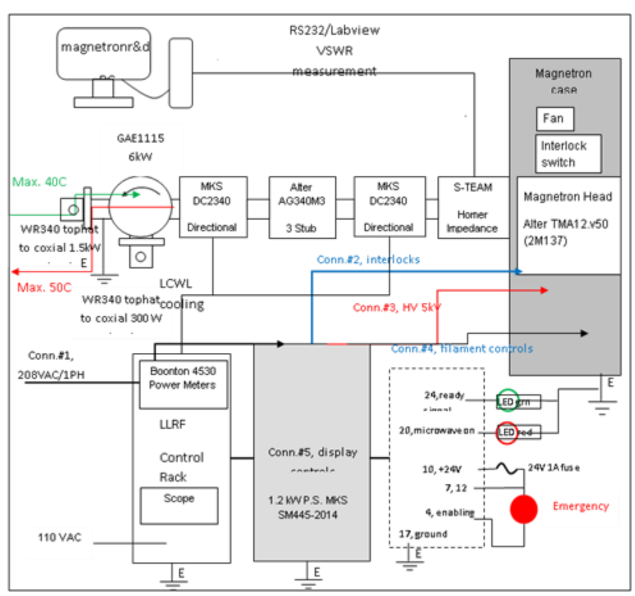

Figure 2: Circuit diagram of Alter magnetron test to a matched load for Rieke diagram measurement.

The initial test was carried out into a matched load only. However two WR340 isolators purchased from Richardson Electronics did not meet isolation specification due to a mismatch of the built-in water load. Instead a WR340 circulator from Gerling was used with an adaptor to an N-type high power load. The characterization of the magnetron input/output parameters can be measured without too much reflected power back to the magnetron head that could trip the magnetron body interlock thermostat.

PRELIMINARY TEST RESULTS TO A MATCHED LOAD

The first measurement of the power spectrum around 2.45GHz as a function of the fraction of maximum output power, roughly as the reference level in %, was done by changing the Pulse Width Modulation (PWM) of the switching power supply on the front knob. As shown in Figure 3, a 90-100% of output power level gives more monotonic spectrum which is a suitable working point for the frequency lock.

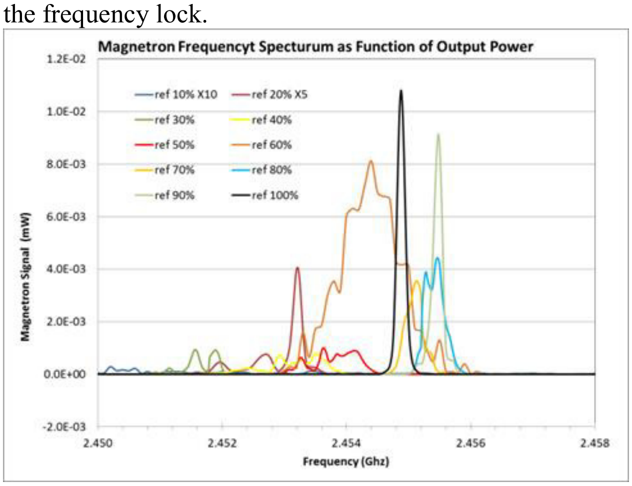

Figure 3: MKS TMA12 magnetron power spectrum measurement to a matched load through a WR340 coupler.

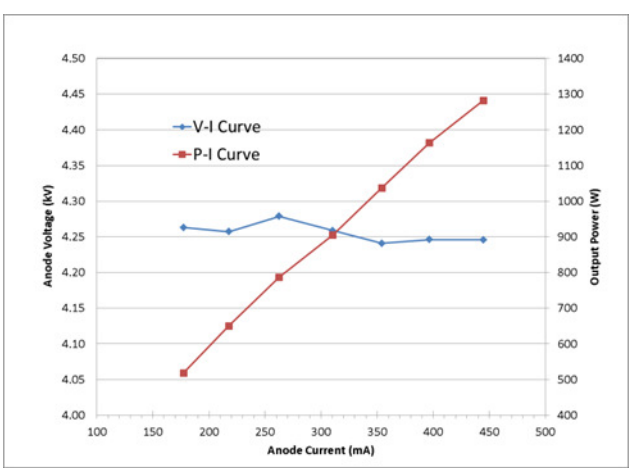

Figure 4: V-I and P-I curves of TMA12 magnetron.

A nearly flat anode V-I curve was observed for output power from 518W to 1282W as shown in Figure 4, indicating a constant voltage mode of power supply operation and a nearly linear response of P-I curve.

The magnetron operates at nearly 70% of electronic efficiency as shown in Figure 5, close to its design parameter of this type of magnetron head. The frequency pushing by the anode current is about 17MHz in this power range as shown in Figure 6, much larger than a -30dB injection signal can be locked bandwidth which has been studied in Ref [4]. Then a frequency lock for the amplitude control will be designed by using both trimming up the magnetic field [2] and tuning a reactive load [4].

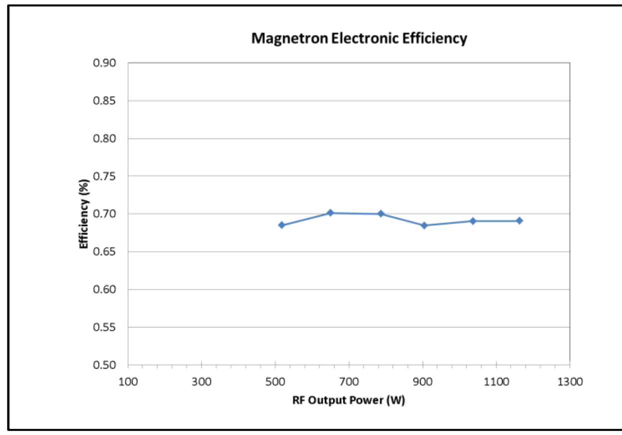

Figure 5: Electronic efficiency in operation parameter range.

The frequency pulling effect by the VSWR changed from 1.2 to 1.7 is about 4MHz from the measurement data in Figure 7. More parameter scans are going to be done in order to obtain a more comprehensive data tables for generating the constant power and frequency contour lines in the Rieke diagram.

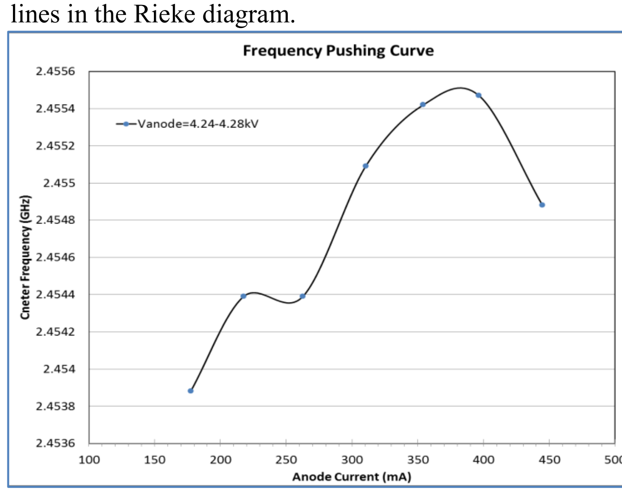

Figure 6: Frequency push curve by anode current change.

High frequency noise on the anode current was directly measured on the switching power supply current monitor. A FFT spectrum indicates that the noise peak is at 84kHz, second harmonic of the switching frequency at 42kHz. This noise figure could finally affect the phase lock performance [1, 3, 4], so an alternative push-pull type DC

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power supply will be evaluated for the next phase of tests to lock RF and SRF cavities.

WORK PLAN IN NEXT TWO YEARS

Under the funded SBIR Phase II and the CRADA between JLab and Muons Inc, we are going to develop two LLRF controllers, one for 2450MHz magnetron system and one for 1497MHz. Both of them will be designed and built based on the architecture of the existing JLab digital LLRF system. We are going to complete the prototype 1497MHz, 13kW CW magnetron and using the test results from the 2450MHz system in the first year to develop the second controller for the high power tests of the prototype 1497MHz magnetron in the second year.

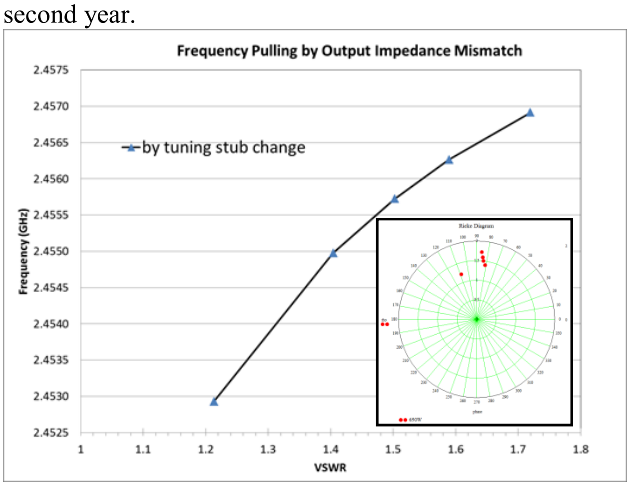

Figure 7: Preliminary frequency pulling curve measured by one stub change only on the output waveguide.

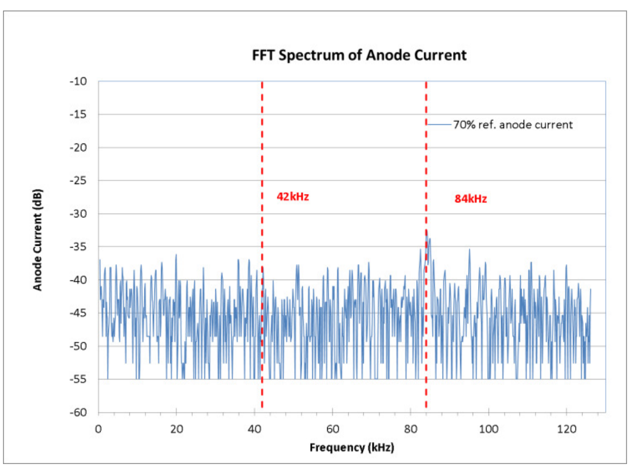

Figure 8: FFT spectrum measured directly by TDS2014B scope from magnetron power supply anode current monitor.

LLRF CONTROL SPECIFICATION

The preliminary top level specification for the LLRF controller is based on the document [5] and Simulink simulation results [2], the carrier frequency of either 2450MHz or 1497MHz can be easily changed via the Local Oscillator (LO). In Table 1, we list the high level parameters for the application of CEBAF SRF cavities and the magnetron test stands that are under the development.

Table 1: Top level specification for magnetron controllers

Cavity RF field regulation	**Response (< / > 1 sec)**
Phase stability (corr.) rms.	0.24^{o} / inf.
Phase stability (un-corr.) rms.	0.5^{o} / 3.0^{o}
Amplitude (corr.) rms.	2.2×10^{-5} / NA
Amplitude (un-corr.) rms.	4.5×10^{-5} / NA
Set point resolution amp/phase	0.1% / 0.1^{o}
Nearby cavity mode rejection	digital
PID gains (K_P, K_I, K_D)	Programmable independent to set point
Latency excluding cable, magnetron, waveguide	<600 ns
Modes of operation and loop switch	Pulsed / CW / Open / Close
External input sync (>10kHz BW)	For fast feedback and feed forward
Carrier frequency	1497 / 2450 MHz
Bandwidth (-3dB)	1MHz
Clock reference frequency	10MHz
IF frequency (TBD)	70MHz@ 0dBm SMA
LO frequency	Carrier-IF @TDB
Cavity Q_{load}	$0.8\text{-}3.2\times10^{7}$
RF Power from magnetron	13kW (1dB comp. 14kW satu. 20dB dyna.)
Cavity microphonic max detune	4Hz 1σ, 24Hz 6σ
Lorentz Force Detune LDF max	2 Hz/(MV/m)^2
LLRF Control System	**Same as C100's**
Diagnostic / Buffers	P_f/P_r/P_t/ I&Q/errors
Pulse mode for bunch trains	<1kHz, 1-100% Duty
Feed forward & adaptive	For pulsed mode only
SEL mode for LDF & auto-track	auto-tune
High Power Interface	**Modify from C100's**
Cathode voltage	6 Analog outputs (100kHz -10 to +10V) Variable gains
Magnet trim coil current	
Anode voltage	
Anode current	2 ADCs 16 bit 1MHz -10 to +10V
Magnetron RF injection	
Control and interlock	**Same as C100's**
Resonance control	Stepper motor and Piezo
Interlocks	BL and WG Vacuums
	Windows arc and temp
Cavity heaters	8, 40-80W each

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