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MAGNETRON R&D TOWARD THE AMPLITUDE MODULATION CONTROL FOR SRF ACCELERATOR*

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Abstract

The scheme of using a high efficiency magnetron to drive a superconducting radio frequency (SRF) accelerator cavity needs not only injection phase locking but also amplitude modulation to compensate for the cavity's microphonics, which cause the cavity voltage to change, and for the variation of the beam current. To be able to do a fast and efficient modulation and to compensate the frequency pushing effect due to the anode current change, the magnetron's magnetic field has to be trimmed by an external coil [1]. To facilitate this, a low eddy current magnetron body has been designed and built [2-4]. This paper will present the analytical prediction, simulation and experimental results of a conventional 2.45 GHz magnetron on the test stand. In addition, the progresses on the injection lock to a matched load, copper cavity, new 1497 MHz magnetron prototype, and the 13 kW high power magnetron test stand development and newly built low level RF (LLRF) controller for the amplitude modulation will be reported.

INTRODUCTION

A magnetron R&D program with the aim of replacing the operating CEBAF 5-13kW, 1497MHz CW klystron systems and other applications has been developed [5]. Since the first demonstration of injection phase locking a magnetron to drive to a SRF cavity at 2.45GHz [6-7], a dedicated 2.45GHz magnetron test stand has been developed at JLab [8]. In addition to the injection phase lock using the magnetron frequency pulling feature, a new amplitude control scheme based on modulation of the magnetron working point, following the frequency pushing curves, has been proposed [1]. Using an industrial heating magnetron at 915MHz as an example, with a 2.5% change of magnetic field together with the anode voltage increasing proportionally, a -3.5dB change in magnetron output power can be achieved. With a 10% trimming of the working point, the magnetron could be used as a back-injection linear amplifier satisfying the RF power requirement for microphonics, beam loading and cavity voltage regulation for a superconducting RF accelerator. Due to the microphonic vibrations and variation in beam loading cavities in CEBAF often operate at less than 40% of the klystron saturated power level. Alternative schemes for amplitude modulation of the power to the cavity such as phase modulation or the vector sum combining of two magnetrons would result in less than 30% efficiency in the same conditions [5]. In those schemes the actual magnetron output power is not reduced and the reflected power from the SRF cavity will be dissipated in the circulator loads and wasted.

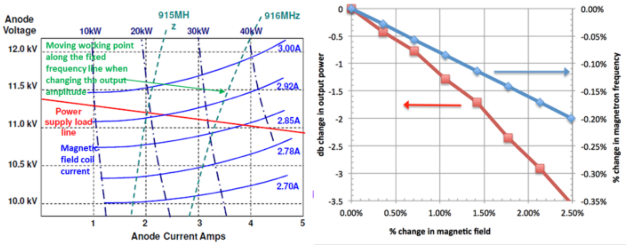

Figure 1: Left: Typical I_a-V_a, P-I_a, F-I_t curves of a 915 MHz magnetron with the working point tuneable by the magnetic field trim-current I_t following the constant frequency line F [9]. Right: Magnetic field trimming curves for lowering the 915MHz magnetron output power (red) and pushing to lower frequency (blue).

2.45 GHZ MAGNETRON TEST RESULTS INTO A MATCHED LOAD

Injection phase lock of the magnetron output has been tested into a coaxial matched load through two WR340 circulators which have more than 55dB total isolation from forward to reflected power. The test stand configuration for this test is shown in Fig. 2. A WR340 waveguide phase shifter was used for the magnetron frequency pulling measurement. The low level RF front-end and digital controller have been installed. A new copper cavity with water cooling and a WR340 waveguide coupling on the cavity flange will be installed soon to demonstrate control of the resonant cavity field.

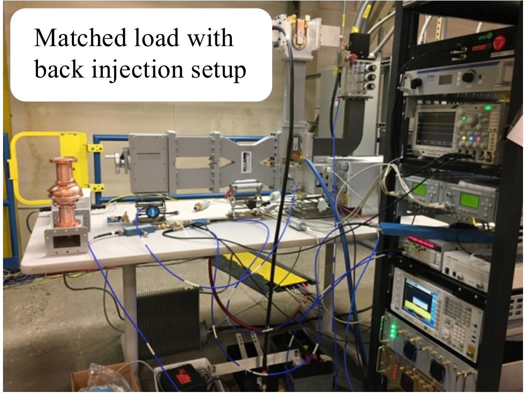

Figure 2: 2.45GHz, 1.3kW CW magnetron R&D test stand developed at JLab.

The phase injection locking test showed a good agreement with the Adler equation which was modified by Chen [10], with a pushing angle α:

$$\sin\emptyset = 2Q_L cos\alpha\sqrt{\frac{P_{out}}{P_{inj}}\frac{\omega_0-\omega_i}{\omega_0}} \tag{1}$$

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Where, P_{inj} is locking power, P_{out} is output power, Q_L is the loaded Q of the magnetron, ω_i is the angular frequency of the injection signal, and ω_0 is the instantaneous natural angular frequency of the magnetron. $\alpha=74.5^o$ was obtained by fitting Equ. (1) with measured data as shown in Fig. 3, right.

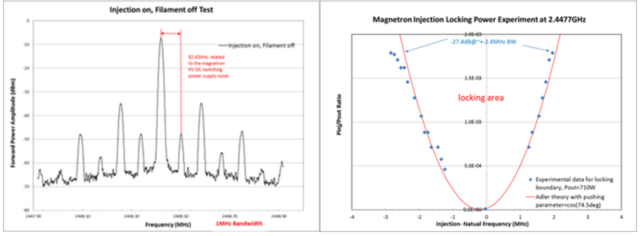

Figure 3: Left: magnetron output power spectrum with back injection on and filament off. Right: injection frequency locking range and power measurement.

In order to get a clean and stable injection phase lock, as shown in Fig. 4, tuning the filament off is desirable since the cathode can sustain RF power down to the 200W level by the electron back bombardment without tripping off the fault protection of the anode power supply. A special filament control box has been built to be able to control the AC filament power supply independently. In reality, a DC filament power supply may be preferred for noise reduction and an easy start-up.

As can be seen in Fig. 3 left plot, a back injection signal level of -27.4dB (1.29W input with 710W of output power), phase locks the magnetron frequency within a bandwidth of ±2.4MHz (right plot) with a nearly 58dB of signal to noise ratio (left plot), except the sideband noise signals generated by its commercial DC switching power supply in which the switching frequency is at 82.45kHz. The typical locked phase error at centre frequency (injection~natural) is 0.05^o RMS, while at the 2.4MHz bandwidth edge it is 0.44^o RMS.

We have found that the injection phase lock is much stronger than a FM lock (Fig. 5, left), also measured the magnetron I-V and I-P curves with filament off (Fig. 5, right) as well as the frequency pushing and pulling curves in Fig. 6. They are essential data to be used in the digital controller for the lookup tables. Frequency pushing at low power has to be compensated by trimming the magnetic field and the anode voltage.

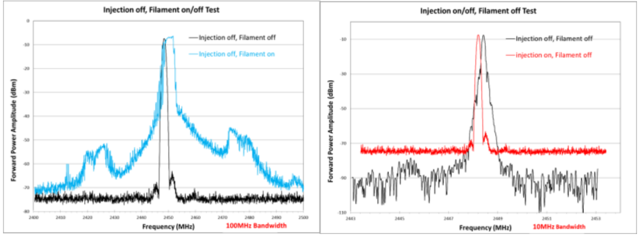

Figure 4: Left: Power spectrum recorded at 100MHz bandwidth without injection with filament on (blue) and off (black). Right: Power spectrum recorded at 10MHz bandwidth with filament off but with injection off (black) and injection on (red).

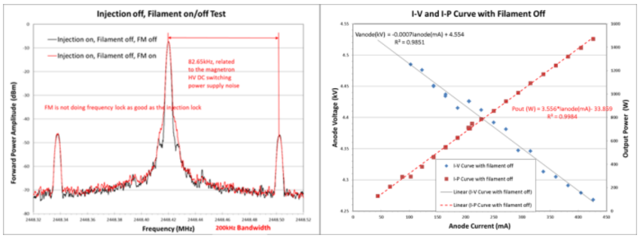

Figure 5: Left: Zoom-in view of Figure 3 left, and also using a frequency modulation scheme (FM) for the phase lock. Right: I-V and I-P curves with their linear fits.

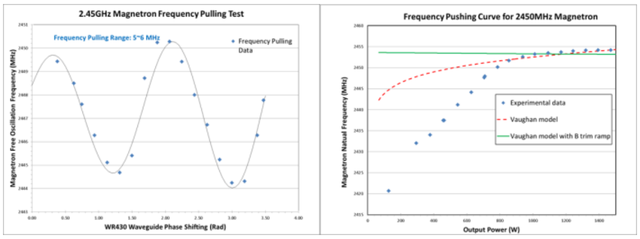

Figure 6: Left: Frequency pulling measurement data. Right: Frequency pushing measurement data and its comparison with the Vaughan model calculated by MathCAD.

TRIM COIL MAGNETIC FIELD SIMULATION AND MODULATION EXPERIMENT

A special design of a trim coil for the 2.45 GHz magnetron has been carried out. A particle in cell (PIC) simulation has been performed first to confirm the scaling formula [11] regarding the magnetron free oscillation frequency f which should scale as with $f=4\pi nV_a/(r_a^2B)$, where r_a is the magnetron anode radius, V_a is the anode voltage, B is magnetic field, and n is the magnetron vane number. As shown in Fig. 7, the frequency is locked at 2.467 GHz. As the magnetic field increased, but V_a/B=constant, only the starting time has slightly changed. This would not affect the CW and long pulse type RF operation since it only happens at <100ns time scale. Then the magnetron output power should follow the $\Delta P/P=-3\Delta V_a/V_a$ law when the frequency f is locked [11].

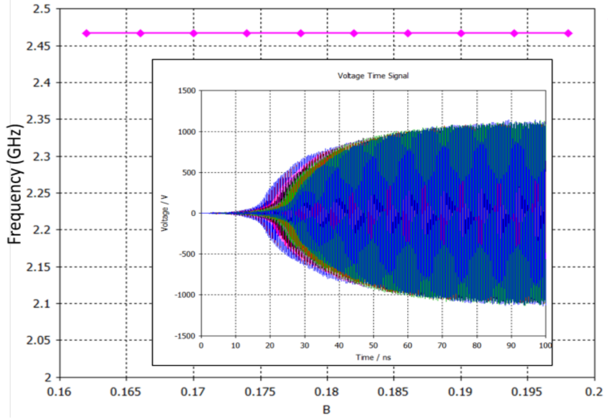

Figure 7: CST particle-in-cell simulation of 2.457 GHz magnetron with the magnetic field trimmed from 0.162T to 0.198T and anode voltage amplitude increased proportionally from -3.87kV to -4.73kV.

A separate magnetostatic simulation has also been performed on the magnet with a pair of bucking coils added into the inside corner space of the iron return yoke, as shown in Fig. 8. A total of 700A-turns are needed in order to trim the permanent magnetic field at 0.18T by ±10%. This simulation model includes also the conical shape of focusing pole pieces in order to calculate the field concentrated at the electron spoke location more precisely. Some used cooker magnetron heads have been collected and cut open to verify the geometry.

A dedicated experiment to modulate a single trim coil has been carried out on the bench. Up to 1kHz modulation frequency of a saw-tooth waveform has been applied on the coil (Fig. 9, top). A Hall probe signal could follow the drive current from 50Hz to 1kHz with an AC modulation of the magnetic field of 2.92% at the 50Hz to 1.26% at 1 kHz (Fig. 9, bottom). The mock-up coil used in the experiment was about 202.4 A-turn at the highest filed level.

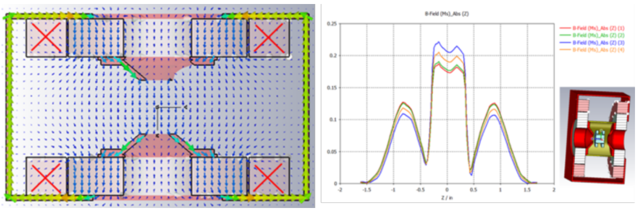

Figure 8: CST simulation of two pancake coils added inside of the magnet return yoke to trim the permanent magnetic field.

1497 MHZ MAGNETRON TEST STAND DEVELOPMENT

To prepare a high power test for the technical evaluation of any magnetron suitable for CEBAF, we have identified an existing klystron test stand which can be refurbished. A new capability of back injection and trimming magnetic field will be added. All other filament, anode and solenoid power supplies as well as the water cooling control circuit and safety interlock system can be shared. A new digital LLRF control chassis has been also produced.

The plan is to install the magnetron body inside of an existing 13kW klystron test bed with a high voltage cage enclosure built around on the top, as shown in Fig. 10. The anode voltage connection is on the top, isolation transformer and filament power supply feeds are supplied from the bottom, cooling water is from the side. Such a stand can be built with a moveable aluminum (non-magnetic) frame, so it can be exchangeable with other klystron tubes where the common power supplies are shared. The ambient magnetization to the performance of ferrite based circulator is not a concern anymore with the aluminum structure.

CONCLUSIONS

Magnetron R&D activities at JLab have made good progress toward the amplitude control of injection phase locked 2.45 GHz magnetron. Injection phase locking bandwidth, power and phase error have been demonstrated, with independent control of the filament, resulting in reduced noise. Modulation of the magnetic field with trim coils up to 1 kHz has been demonstrated. An integrated test with field trimming under control of a new digital LLRF system will be performed soon. An innovative design of a low eddy current magnetron at 1497 MHz, 13kW, that should have even wider control bandwidth is being pursued by Muons Inc. JLab is preparing a new test stand in anticipation of this magnetron tube.

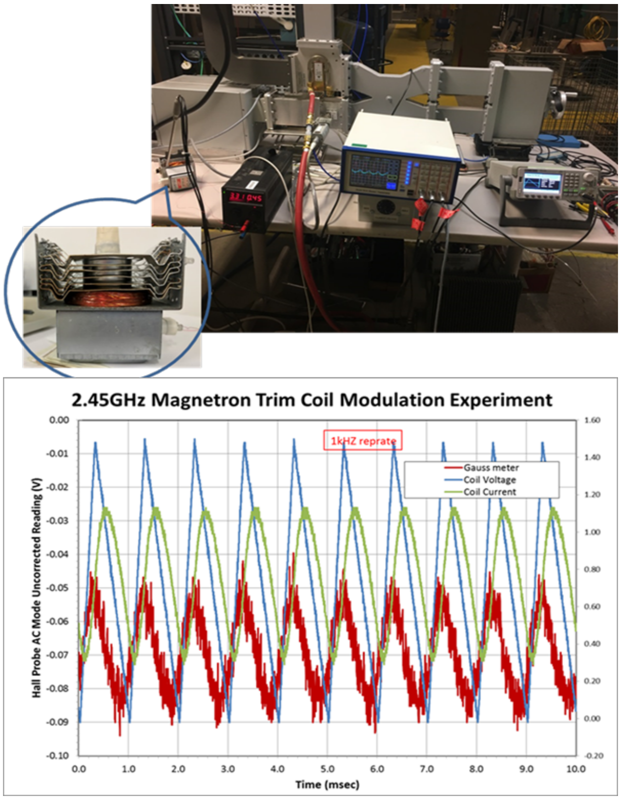

Figure 9: Top: experiment setup for the modulation of trim coil current. Bottom: magnetic field follows the 1kHz modulation of saw-tooth drive current.

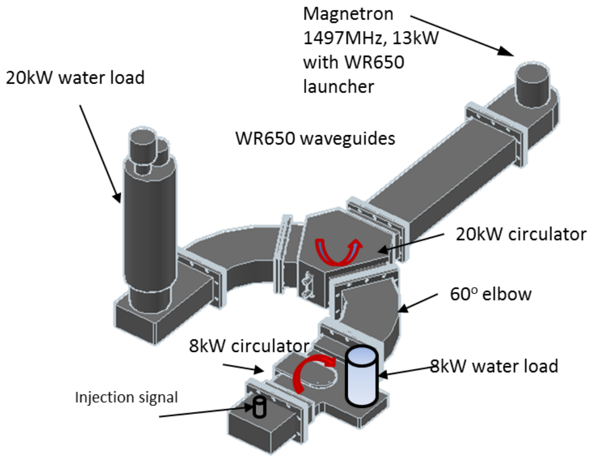

Figure 10: 1497MHz magnetron test stand CAD design with the WR650 waveguide connection to circulators and water loads.

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