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MAGNETRON R&D FOR HIGH EFFICIENCY CW RF SOURCES OF PARTICLE ACCELERATORS*

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Abstract

A proof of principle experiment carried out at JLab's magnetron R&D test stand has demonstrated a -25dB injection signal to phase lock a 2.45 GHz 1.2 kW CW magnetron within 2.1 Hz of root mean square deviation (RMSD) value with the optimization of magnetic field trimming of ±25% in order to overcome the frequency pushing of more than 4 MHz in the RF power output range of 45-100%. In addition, a test stand for a newly built 1497 MHz, 13 kW, CW magnetron prototype is ready for the high power injection test with outcome aimed for the CEBAF klystron replacement. Based on these R&D results, a 915 MHz, 2×75 kW CW commercial heating type magnetron system is being developed as high efficiency (>80%) RF source to drive an electron linac for industrial applications.

INTRODUCTION

Magnetrons typically have a higher electronic efficiency than conventional klystrons and solid state amplifiers. We have compared the efficiencies from available commercial tubes [1] and developed an R&D program to study critical techniques for 915 MHz, 1497 MHz and 2450 MHz magnetron application with aim of driving superconducting and normal conducting accelerators for scientific and industrial uses at lower cost (<$1/W) and higher efficiency (>80%).

Since the first demonstration of injection phase locking to drive a superconducting cavity [2, 3], we have concentrated on a scheme of amplitude modulation to compensate for the cavity's microphonics, frequency change, variations of cavity voltage and beam current loading. To be able to do a fast and efficient modulation and to compensate for the frequency pushing effect due to the anode current change, the magnetron's magnetic field can be trimmed by an external coil [4]. The first open loop manual modulation to trim coils by DC voltage was carried out for the proof of principle experiment into a matched load. A closed loop experiment to stabilize an RF cavity's voltage will be done next. The rate at which the field can be modulated is limited by the self-inductance of the coils and the magnetic circuit of the tube as well as eddy current in the tube body. To address this, a low eddy current, low external Q 1497 MHz, 13kW CW magnetron has been designed and prototyped [5, 6]. Meanwhile, we have procured an AMTek Microwave 915 MHz, 75 kW, CW industrial oven type magnetron transmitter for the injection and power combining R&D. Tests to compare phase locking and power combining performance with use of silicon-controlled rectifiers, switching and klystron power supplies will be carried out. The first application would be demonstration of a system capable of driving a 1MV, electron linac for environmental remediation and material treatment, scalable up to 1 MW.

UPDATES ON 2.45 GHz MAGNETRON R&D TESTS

Injection phase locking of the magnetron output has again been demonstrated into WR340 to a coaxial matched load and a normal conducting (NC) RF cavity. The back injection signal of a few Watts is supplied through two WR340 circulators having more than 55 dB total isolation from forward to reflected power. The test stand configuration for this test is shown in Fig. 1. The WR340 waveguide phase shifter and stub tuner used previously have been removed to minimize frequency pulling by output reactance and maximize it by back injection. After a demonstration of injection phase lock to the cavity frequency at a fixed wall loss of 633 W and with signal to noise ratio of 39.3 dB at 262 Hz sidebands, we changed back to the broadband load for the amplitude modulation test with trim-coils. It was determined that filament off condition can maintain the output power with reduced efficiency by ~5% as indicated by Fig. 2. The electron emission is sustained by spent energy electrons returning to the cathode, with injection on, the S/N ratio is much improved due to reduction in thermal noise from the filament. The injection lock did not reduce the electronic efficiency any further. In order to accommodate the addition of trim-coils, a small amount of material was machined off yoke frame to make room for the coil pancakes and this changed the I-V and I-P characteristics as shown in Fig. 3.

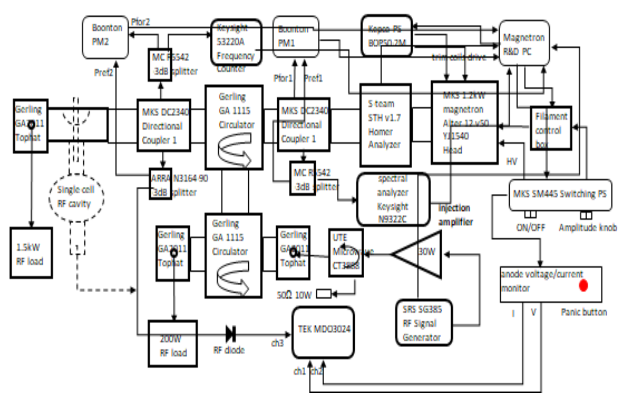

Figure 1: Schematic of 2.45 GHz, 1.2 kW CW cooker type magnetron R&D set up for an RF cavity/matched load test.

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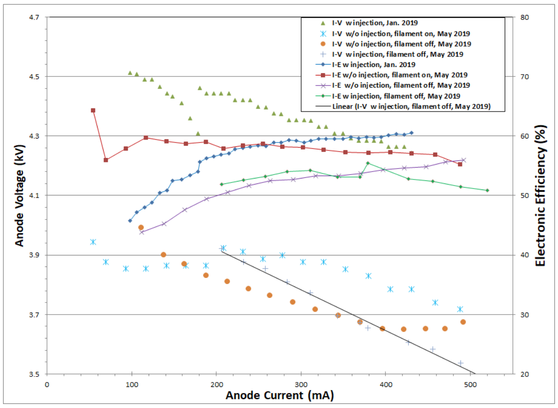

Figure 2: I-V and I-E curves measured with matched load.

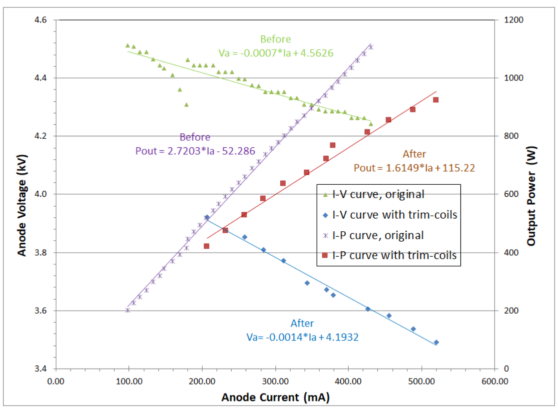

Figure 3: Measured I-V and I-P curves before (Jan. 2019) and after modification with trim coils (May 2019) and their linear fits. All measurements are with injection on and filament off.

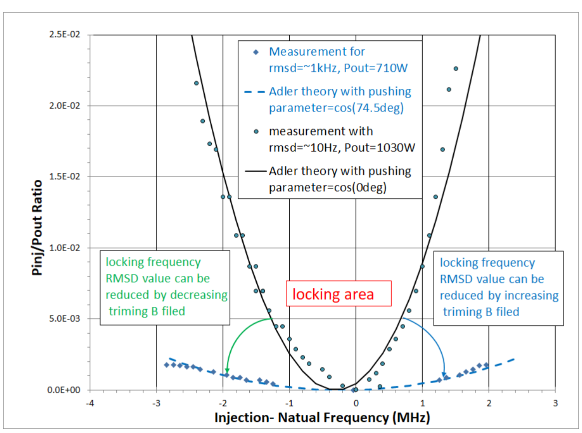

Figure 4: Injection power verses frequency locking bandwidth measured on YJ1540 magnetrons and their data fitted to the Adler/Chen equation (1).

The tuning slope of $\Delta P_{out}/\Delta V_a$=-3.89 (W/V) on the original structure was changed to -1.15 (W/V). The higher-power commercial magnetrons already use electromagnets so this would not be a problem in those cases.

Adler equation [7] stated the injection locking phase ϕ which was later modified by Chen [8], with a pushing angle α is:

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

where, P_{inj} is locking power, P_{out} is output power, Q_L is the loaded Q of magnetron, ω_i is the frequency of injection signal, and ω_0 is instantaneous natural frequency of magnetron. In Fig. 4, the black curve is obtained by fitting Equation (1) with α=0° to the measurement data which was with the trim-current being zero and keeping the RMSD values within the parabolic locking boundary in ≤10 Hz. Fitting to the data with a lower injection power (blue curve, α=74.5°) for the same locking bandwidth would lead to less phase stability in higher RMSD value, like ≤1kHz. However, the trimming current give us a third knob to retune the locking stability back to Hz range while still using a reasonable injection power like the measurement data shown in Fig. 5.

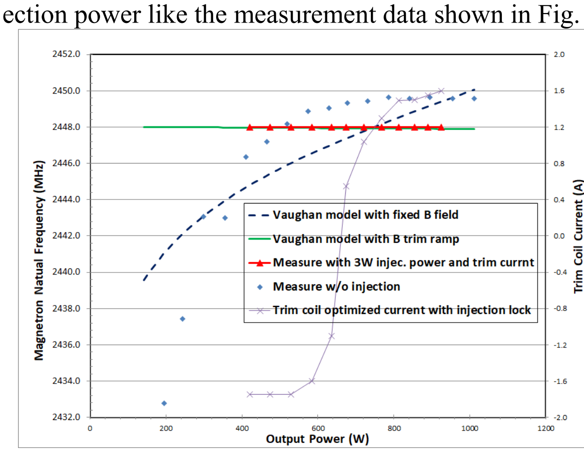

Figure 5: Natural frequency pushing of a magnetron, measurement verses Vaughan analytical model [9], and its optimized trim current.

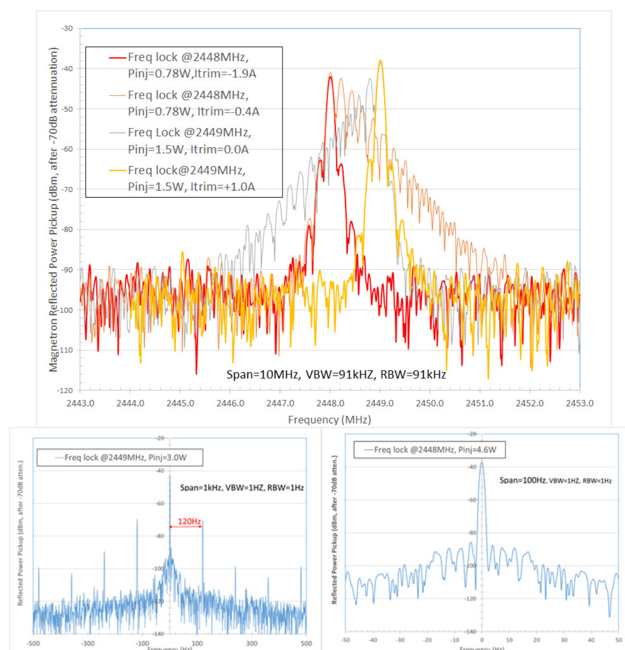

Figure 6: Top: Injection phase locked power spectra and their sidebands suppression with trim coil current optimization over 10 MHz span. Bottom: Zoomed-in spectra in 1 kHz span (left) and 100 Hz span (right).

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As indicated in Fig. 5, a combination of back injection and trimming the magnetic field can overcome the frequency pushing from 45% to 100% of magnetron output power with a locked frequency error ≤2.1 Hz RMSD value by ramping the trim-coils from-1.75 to +1.6 A. The locked frequency performance can be observed by the spectrum sideband excitation (Fig. 6) and the frequency counter reading on the forward power. Once a strong phase lock is optimized, the frequency change is only at the Hz level and the sidebands are clearly suppressed, except for -27.6 dB peaks at ±120 Hz of noise from the mains. This could be reduced further by active feedback from digital controller. There are no sideband excitations within 100 Hz bandwidth indicating that we could use this controlled source for a high power vertical test of a superconducting cavity again [2] but with a nearly critical coupling.

TRIM COIL BENCH MEASUREMENT

Two 360-turn coil pancakes have been designed and built to fit inside corners of YJ1540 magnetron yoke without obstructing the cooling of the anode (Fig. 7 bottom left). The electrical current can be trimmed ±2 A resulting in ±31% AC variation of the 0.16 T of DC ferromagnetic field according the CST simulation as shown on the top right of Fig. 7. The modulation measurement on the modified YJ1540 magnetron confirmed that both eddy current in the magnetron copper body and the proximity effect of litz-wire coils reduce the effective AC magnetic field at higher frequency [10] as indicated at the bottom right of Fig. 7. However useful modulation levels are still achieved up to 1 kHz covering the range of interest for most microphonics.

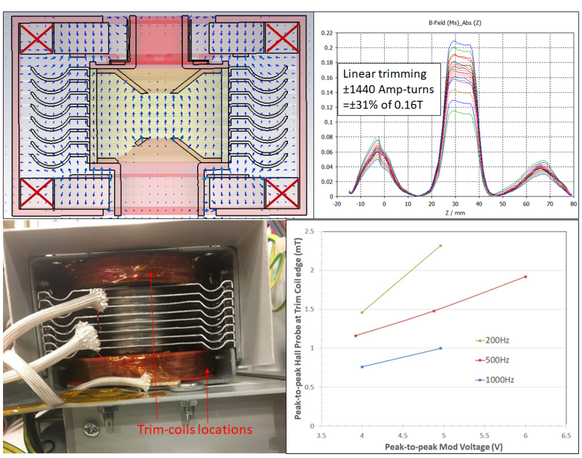

Figure 7: Top: CST simulation of trim coil modification. Bottom: Trim coil mount and modulation measurement.

1497 MHz MAGNETRON TEST STAND

Two 1497 MHz, 13 kW, CW magnetrons one copper, one a stainless steel/copper hybrid anode structure have been designed by Muons Inc and prototyped by its partners [6]. These are together with one solenoid and one trim-coil to be delivered to JLab soon for injection and digital control in full power tests. To prepare for a low-noise, non-cut-off filament operation at low output power, an isolation transformer and a DC power supply with fiber-optic control have been purchased to be installed inside of the existing klystron HV cabinet. A moveable frame has been built to support circulators and water loads external to the cabinet as shown in Fig. 8.

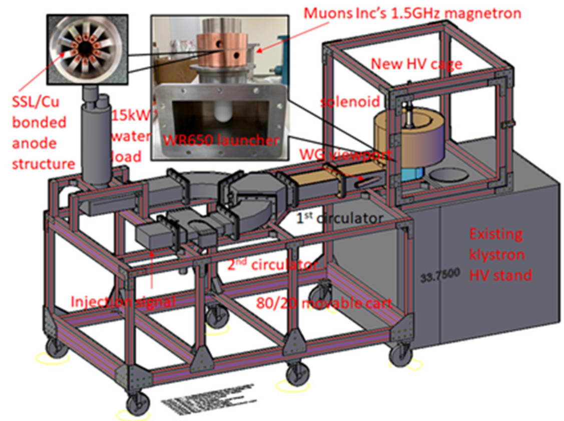

Figure 8: 1497 MHz prototype magnetron test stand developed using existing 13 kW klystron power supplies.

HIGH EFFICIENCY SOURCE DEVELOPMENT FOR SCIENCE AND INDUSTRY

With funding support from the DOE Accelerator Stewardship program, we are also using commercial type magnetrons to demonstrate the goal of 1 MW of combined RF power at 915 MHz with >80% efficiency. The power injection and LLRF digital control systems for noise reduction from filament heating, power supply ripple and the optimization with trimming magnetic field will be critical techniques for building and programing the state-of-art digital controllers developed from our SRF projects [11] to be implemented on a commercial AMTek magnetron transmitter (Fig. 9). The end goal is to transfer this technology into industrial applications with user-friendly interfaces.

Rather than using binary Magic-Tees, new power combiner concepts are being investigated for low cost and high efficiency usage. One approach consists of a zero-dB coupler with a TM01 mode circular waveguide radially connected to the outputs of multiple magnetrons [12]. A second approach is based on the concept by Bostick [13], where odd number of magnetrons can be operated in parallel by using waveguide iris couplers.

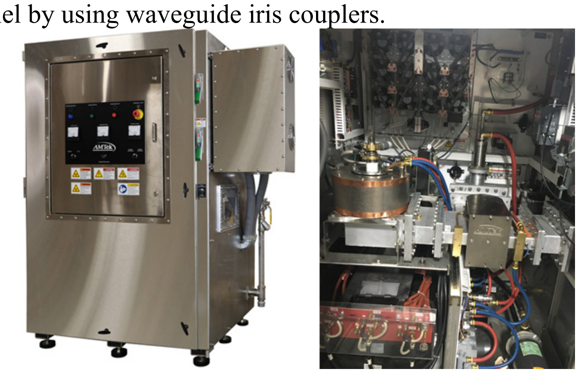
Figure 9: AMTek 915 MHz, 75 kW CW magnetron transmitter to be used as accelerator applications.

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CONCLUSIONS

The R&D experiments on a 2.45 GHz magnetron have clearly demonstrated that such a device can be used as an RF source for accelerator cavities with injection power less than -25 dB. The development of high efficiency magnetrons at 1497 MHz offers an alternative to the existing klystron sources used in CEBAF. Using a commercial 915 MHz magnetrons with optimized injection locking, field trimming and digital LLRF control offers a pathway to a cost effective MW class RF source.

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