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

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Abstract

After the demonstration of using high efficiency magnetron power to combine and aim to drive a radio frequency accelerator at 2450 MHz in CW mode [1], we have used trim coils adding to a water-cooled magnetron and three amplitude modulation methods in an open-loop control to further suppress the 120 Hz sideband noise to -46.7 dBc level. We have also successfully demonstrated the phase-locking to an industrial grade cooking magnetron transmitter at 915 MHz with a 75 kW CW power delivered to a water load by using a –26.6 dBc injection signal. The sideband noise at 360 Hz from the 3-Phase SCRs DC power supply can be reduced to –6.2 dBc level. Their power combing scheme and higher power application to industrial accelerators are foreseeing.

INTRODUCTION

The industrial heating type magnetrons at 915 MHz operated in CW mode have more than 90% of DC to RF efficiency and making cost of effective ~1 $/W market value [2]. Under the accelerator stewardship program, we have set up a test stand intending to drive radio frequency accelerators for 1–10 MeV electron beam energy and up to 1 MW of beam power applications [3]. Since May 2019, the first AMTek® 75 kW magnetron transmitter has been setup as a high powers test stand at Jefferson Lab (JLab) [4]. Due to the COVID-19 pandemic restrictions, the experimental progress was mostly made at 2450 MHz RF systems at JLab and General Atomics (GA) and with help of summer interns of Research Experience for Undergraduates (REU) students [1]. The utility connections and Programmable Logic Controller (PLC) modification had been made to the first unit. A second 75 kW transmitter unit has been delivered to JLab, we are going to combine these two units by a WR975 waveguide magic-tee to have 2×75 kW of power available with the injection phase-locked performance for both electron linac booster and the SRF accelerator.

INJECTION PHASE-LOCK DEMONSTRATION OF 915 MHz MAGNETRON

After first tuning on the 75 kW magnetron in manufacture control mode, we have measured the anode I−V and I−E curves with a careful high voltage reading check and a TRL calibration for the RF power meters. The injection phase-lock scheme has been set up as in Fig. 1 by using double isolation of two WR975 circulators. A special care to the bench measurement to have the optimized circulator/water load performance in isolations, transmissions reflections (particularly on the primary circulator) is important to have a best S/N ratio for the injection signal.

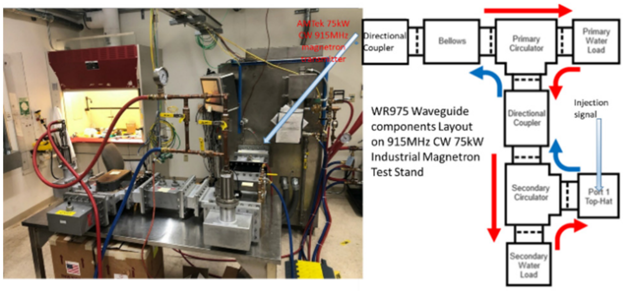

Figure 1: AMTek® 915 MHz, 75 kW CW magnetron test stand at JLab with back injection layout for phase-lock. Blue arrows indicate the injection path. Red arrows direct the RF power to primary and secondary water loads.

Table 1 lists the optimized bench measurement data of this waveguide circuit before and after the waveguide assembly. Removing excessive iron plates from the circulator magnet shunts and relocating them are critical technique in the magnetic field trimming [5].

Table 1: TRL S-parameters measurement at 915 MHz after trimming on circulator magnet shunts with the Port 2 at output power direction as indicated in Fig. 1. The last row data was for fine-tuned assembled system at 912.5 MHz.

Circulator water load pair	**Isolation S12 (dB)**	**Reflection S11 (dB)**	**Reflection S22 (dB)**	**Transmission S21 (dB)**
Primary	-43.15	-22.73	-22.80	-0.15
Secondary	-17.13	-15.63	-18.08	-1.40
Combined	-57.04	-14.71	-22.85	-1.90
Assembled	-53.22	-15.51	-23.46	-1.59
912.5 MHz	-51.05	-16.00	-23.82	-1.70

We have first observed locking state at 65 kW level as shown on a spectrum analyser (Fig. 2). Once locked at 75 kW level, a frequency counter could monitor the frequency variation being only within a sub-Hz range, indicating a strong lock performance. The injection power is at −26.6 dBc level. We have expected major 360 Hz noise peaks with 60 Hz intervals coming from the 3-phase SCR

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DC power supply. The AMTek® unit made for cooking industrial does not need a RC filter and the anode current thus the power output are controlled by solenoid and cathode filament currents. Only choice we have now was to reduce the filament current at 75 kW level from 88 A to 65 A to have an optimum ~−5 dB noise reduction (as seen in Fig. 3). Its further reduction had increased noise level and made the phase locking unstable. We have also measured I−V and I−E curves, as shown in Fig. 4, indicating a >90% of DC to RF conversion efficiency, even in the locking state. We need further to confirm those high efficiency numbers by a calorimetry technique. The negative I-V slop is typical to a magnetron tube. No further attempt yet to trim the solenoid current to push the frequency up to 915 MHz, since the solenoid coil is in series connection to the anode current, anyway to low its set point would trip the anode current overflow.

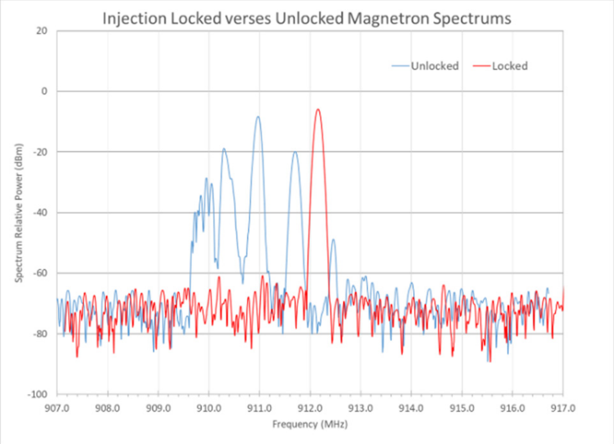

Figure 2: First record of magnetron spectrums at 65 kW before and after injection phase-lock at 10 MHz bandwidth.

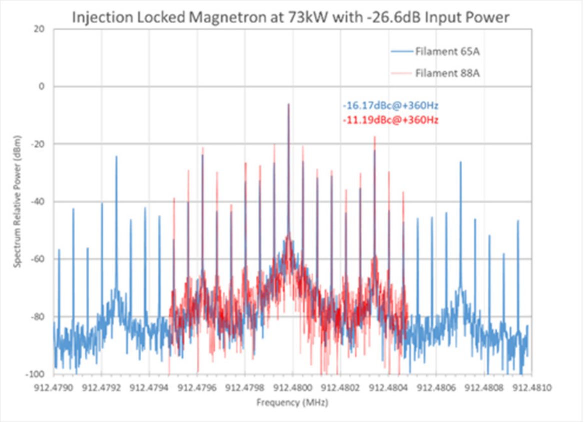

Figure 3: Injection locked spectrums at 1 Hz of RBW and VBW to compare the noise reductions at 360 Hz.

Unlike our RF test stands at 2.45 GHz, the layout of two circulator/water load pairs are compact assembled, the S11 reflection for 912.5 MHz could not be further reduced due to non-ideal match of water load and the multiple reflections between the circulators in high power operation. Further minimization of S11 refection is more critical to the injection lock performance than the isolation property of S12. However this sub-Hz locking performance indicates that we can use this power source to drive a SRF cavity system with coupling Q of 1×10^6 in less than 0.13° of RF phase accuracy—good enough for the beam energy spread control of an industrial type of accelerator. However, a fast feedback control system on all power supplies of the RF system in a few kHz control bandwidth is necessary to suppress the sideband and microphonic noises. Our further experiment at 2.45 GHz test stand on the amplitude modulation has confirmed this proof of principle and its feasibility.

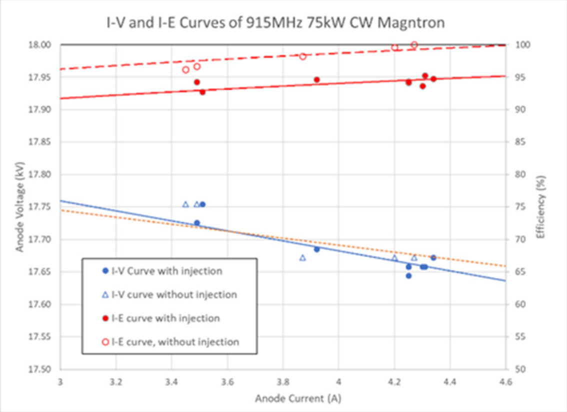

Figure 4: Measured 915 MHz magnetron anode I−V and I−E curves.

AMPLITUDE MODULATION ON PHASE-LOCKED MAGNETRON AT 2.45 GHz

To demonstrate a more effective way to reduce the frequency pushing, typically ~10 MHz range in 20−100% power range for kitchen cooker magnetron as shown in Fig. 5, we have modified a water-cooled magnetron on its cooling block to have more room available for a pair of trim coils installation. Two coils make total 444 turns of AWG #20 copper wire, as shown in Fig. 6 (top inserts). The CST simulation indicates that a ±2 A of bias DC current can trim the magnetic field in the central beam region by ±7.3% (bottom), which is not enough for the 10 MHz nature frequency tuning but is enough for the amplitude modulation in kHz range to further suppress the sideband noise.

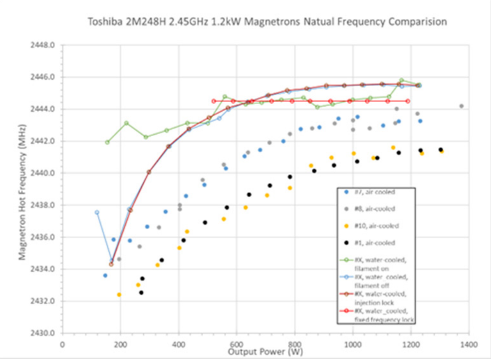

Figure 5: Magnetron natural frequency pushing range on different magnetron heads. A modified magnetron can be injection-locked at sub-Hz frequency level in its upper power range (as shown in red curve).

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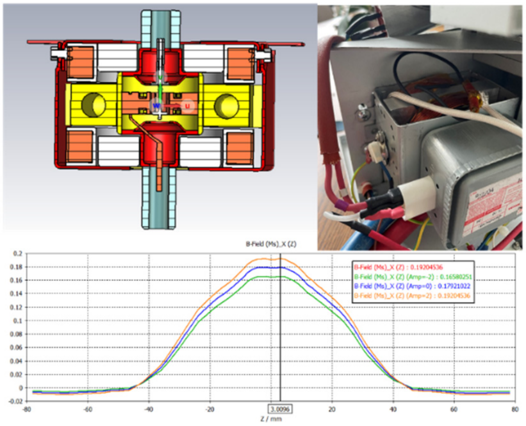

Figure 6: Trim coil modification to a water-cooled magnetron head (top-left) and installation (top-right) and the CST simulation indicating the magnetic field trimming.

After eliminating an injection noise from its 30 W RF amplifier by using a “cleaner” DC power supply with <1.5×10^{-4} rms output current ripple, we have identified the major sideband 120 Hz noise must come from the switching anode power supply. We have used three different amplitude modulation techniques. One is on the anode current of power supply, two is on the injection RF signal, third is on the trim coils current. We have applied nominal 5% of modulation depths in sine waveforms in 120 Hz and a bias of DC current on the trim coils. A typical noise reduction effect can be observed in Fig. 7, an optimum of −1.0 A of DC bias has greatly reduced the noise peaks by 8-12 dBc. Other modulation methods can either reduce or increase the peaks further by 3-4 dBc, all of AMs used were in an open-loop control without adaptive feedbacks yet. A fast digital feedback controller to drive the power supplies for the anode and trim coil currents and RF injection drive is critical for a noise-free RF system operation [6].

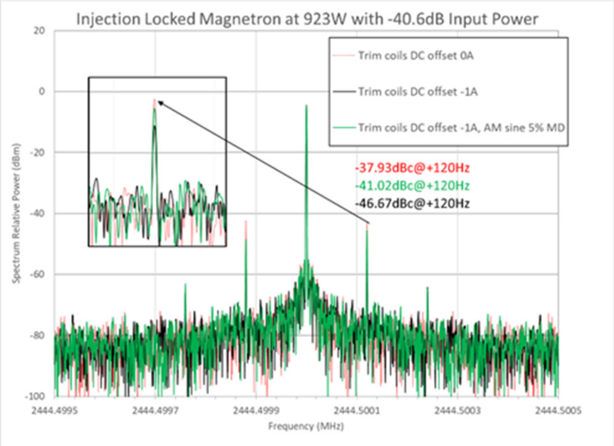

Figure 7: Noise reduction performance on the 120 Hz side band from the anode power supply by using a DC bias and AM modulation on a pair of trim coils.

A typical CEBAF 5 kW CPI klystron has a lower 60 Hz sideband noise at −58.3 dBc as shown in Fig. 8. Our result from the amplitude modulation of trim coils without feedback is not too far from it, but its non-linear control algorism needs to be programmed into the FPGA and PLC logics since the magnetron operates as oscillator than the klystron as linear amplifier [2]. A switching power supply is a better choice for magnetron operation.

POWER COMBINING USING MAGIC-TEE AND INJECTION

Previous power combining experiments by using WR340 magic-tee carried out at GA indicated that a large natural frequency difference between two magnetron heads could cause a low combing efficiency when the water load has a finite reflection [1]. A phase shifter at magic-tee output had to be used for its compensation. However, for the high power application, a phase shifter would bring the whole RF source system cost up. By choosing the best matching pairs in a closer natural frequency pushing range (Fig. 5), and by using the capability of trim coils, we can have more controllability in the magic-tee scheme. A Matlab code has been developed to take account of the natural frequency, external Q of each magnetron and reactive impedance of water load or a RF cavity. The injection locking bandwidth model governed by the magic-tee network s-parameters, Adler-Chen’s instability theory [7], and the trim-coil pushing parameters. The peer-to-peer locking bandwidth could be further increased [8, 9]. We will conduct next experiment at GA by using measured data sets from JLab for the best magnetron head candidates and the optimum controlling parameters. The result will guide our next magnetron power-combining scheme in our stewardship program.

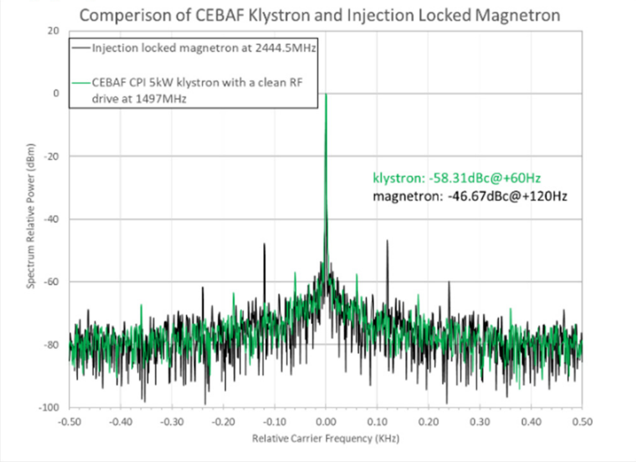

Figure 8: Comparison of sideband noises from a phase-locked magnetron and a 5kW klystron used at CEBAF.

CONCLUSION

A good injection phase-lock performance of 75 kW magnetron has been demonstrated. High power cooking type magnetrons are feasible for the power combining and industrial accelerator application. We are going to improve the injection power and solenoid trimming for further magic-tee type binary 2×75 kW power combing. The amplitude modulation experiment has demonstrated the proof of principle to suppress sideband noise. A smarter digital controller with fast adaptive feedbacks on the magnetron power supplies is critical to the magnetron operation.

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