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# PROGRESS ON MAGNETRON R&DS FOR INDUSTRIAL PARTICLE ACCELERATORS*

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*Abstract*

The magnetron as an efficient RF source for a compact industrial SRF accelerator has been developed. The performance of injection phase lock on two independent magnetron transmitters operated at 915MHz, in CW mode with maximum power of 75kW each has been demonstrated to satisfy this application. This industrial type magnetron has AC transformer and the SCR rectifier on the DC anode power supply. Output power spectrum with phase locking can achieve noise reduction of -21.2 dBc at the 1st 60 Hz, -28.0 dBc at 1st 180 Hz with only -22.6 dBc injection power. Further control studies for 2×75 kW, 915 MHz power combing by WR975 magic-tee at Jefferson Lab (JLab) and for 4×1.2 kW, 2.45 GHz power combing by WR340 magic-tee at General Atomics (GA).

## INTRODUCTION

Magnetrons have been considered as alternative RF sources for superconducting radio frequency (SRF) accelerators since the first demonstration of injection phase lock to an SRF cavity [1]. Since then, commercial 915 MHz magnetrons have been found to be very efficient (>90%) and cost effective (<2$/W) for the industrial accelerator applications [2]. Progress had been made since we started working with US industrial and small business partners [3, 4]. By working on both 2.45 GHz and 915 MHz magnetron systems, we have obtained excellent performance of magnetron phase lock and amplitude feedback controls.

## INJECTION PHASE-LOCK PERFORMANCE OF 915 MHz MAGNETRONS

After first demonstrated injection phase lock to a full power of CW 75 kW on the #1 AMTek magnetron [3], the #2 AMTek magnetron installed in 2022 has achieved a better injection lock performance. As shown in Fig. 1, in the second high power test, an injection power of 415 W (-22.6 dBc) can lock the magnetron frequency at sub-Hz accuracy with ~75 kW power delivery to water load. The sideband noise can be suppressed to -21.19 dBc at 60 Hz and -28.04 dBc at 180 Hz. The Dc-to-RF efficiency is ~95%. A calorimetry measurement using cooling water flow meters and thermometers has further confirmed this efficiency. Comparing to the #1 AMTek magnetron, this unit uses later developed SCR controller from Control Concepts for 480 Vac-3ph transformer with digital zero-crossing phase angle control.

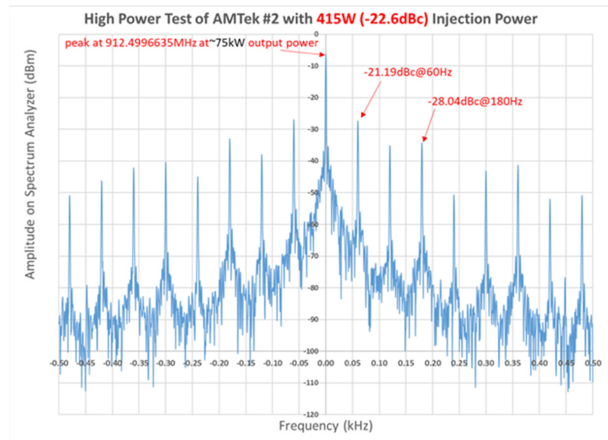


Figure 1: Injection phase locked spectrum at 1Hz of RBW and VBW to compare the noise at 60Hz harmonics on the #2 AMTek magnetron transmitter at 75kW output power.

Magnetron natural frequency push up by 365 kHz was done by increasing the shunt resistor's resistance which caused the solenoid current increase from 4.31 to 5.00A with the same anode current. It is not enough to operate it at 915 MHz, but good enough to bring it to match the #1 magnetron frequency at 912.434 MHz which is -66 kHz away.

The stability of sub-Hz locking performance indicated that we can use this power source to drive an SRF cavity system with coupling Q of $1\times10^6$ in less than 0.13° of RF phase accuracy, sufficiently high for the beam energy spread control of an industrial type of electron accelerator.

## POWER COMBING SCHEME WITH BINARY MAGIC-TEE WAVEGUIDE

We have studied the power combing schemes, with available 125 kW each tube, we can combine 8 of them to get 1 MW. Certainly a combing cluster of 4 or more magnetrons is ideal for the cost and space saving issue. However, after several experimental and simulation studies at GA, we have found a TM010 cavity type power combiner is needed to overcome the beat-wave instability between the cavity and magnetron. A good way to mitigate the beat-wave is to insert a high-power waveguide damper at the beginning of the magnetron start-up, moreover the cavity wall losses yields a lower combining efficiency. We then down-selected the binary combining scheme based on the 4-port magic-tee waveguides which has the system add-on

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waveguide components with one circulator and one water load per one magnetron tube. Overall system including the control is affordable with a performance like a single injection phase-locked magnetron.

We have proposed and prepared such high-power combing tests at JLab and GA. GA is to do the 4x1.2 kW power combining experiment at 2.45 GHz with a goal of developing control algorithm for the magic-tee network. JLab is to do the ×75 kW power combining experiment at 915 MHz as the Year 1's goal. To reduce the risk of failure at high power test, the study of control accuracy and injection lock stability at GA's the low power test stand is important.

As shown in Fig. 2, all high power WR975 components have been procured and expected a late delivery of 150 kW circulator and water load due to a supply-chain delay. We are going to do the 2×50 kW power combining experiment first to reach the cooling limit of 100 kW on water loads. The magnetron output waveguides have been made to accommodate a $\lambda_g/4$ length difference between magic-tee inputs. An analysis of 4-port network has been made for two operational failure cases [5]. In the case of non-prefect 150 kW water load with VSWR of 1.2:1, a maximum return loss of 623 W could reflected to each magnetron. It would compete the back injection power of ~500 W which noise could lead to losing the phase lock. A full power of circulator is needed at the magic-tee's sum port. It would also reassemble the real RF power system to drive a SRF accelerator, its output circulator and water load have to handle a full reflection power from the SRF cavity. In the case of high voltage trip-off on one of power transmitters, the maximum power from other one could be redirected to the differential port toward to injection source. A primary injection circulator and a 75 kW water load are needed to protect the injection circuit which capacity is designed for 1.1 kW at VSWR of 1.2:1 only. The secondary injection circulator is designed to phase lock any single magnetron when other magnetron is off (Fig. 3).

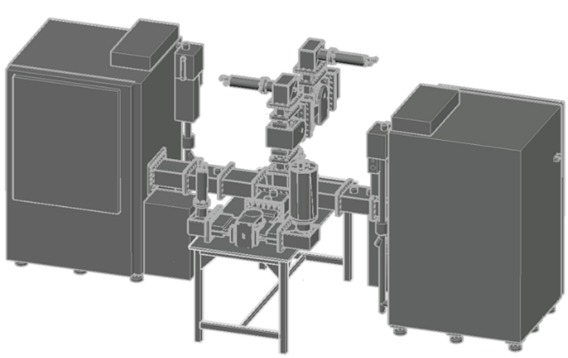

Figure 2: 2×75 kW power combining test stand setup at JLab. Two AMTek magnetron are connected by WR975 magic-tee and circulators and water loads.

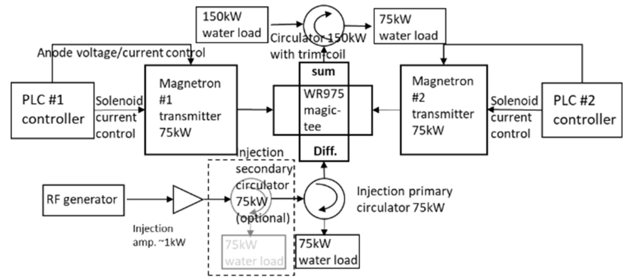


Figure 3: Simplified control layout of Fig. 2 for binary power combing. Secondary injection circulator is designed for the full protection if one of transmitters is tripped off.

Original output power control method on the AMTek magnetron is by lowering the solenoid and filament currents since the tube anode is in series connection to the solenoid coil. Unfortunately, output power at 50 kW level by adjusting solenoid current is not naturally stable, then it is more difficult to do an injection phase lock. To operate magnetron at lower output power, lowering the anode voltage setpoint has been suggested by the tube vendors. We have first tried to change the control angle of the SCR However, a higher DC voltage ripples have been found and caused magnetron tripped with higher harmonic mode jumping. We are going to change transformer tap connections for the next study.

If the 2×75 kW test is successful as planned in Year 1, we are going to do the 4×75 kW test in Year 2.

## INDUSTRIAL COLLABORATION

To demonstrate a compact industrial electron accelerator for the wastewater treatment plant, JLab, GA and InnoSys, Inc have been awarded by several ARDAP funds for a demonstration cryomodule of the Superconducting RF (SRF) cavity integrated with conduction cooling by GM cryo-cooler [6]. The magnetron source has been chosen as the primary candidate of RF source at 915MHz. 25 kW is needed for the design of SRF option at GA and 55 kW is needed for the normal conducting option at InnoSys, Inc.

InnoSys will do the DC switching power supplies development for the 2.45 GHz/915 MHz modules which require feature of 0-100% power scale in constant current mode, Anode voltage arc or overvoltage, tube over temperature or cooling water over pressure protections. Filament and trim-coil have DC current regulations. Smarter controller of power supply will use the FPGA for fast feedback on the anode and trim-coil currents. InnoSys will also help the DC gridded cathode electron gun development for the beam delivery of graded beta section of linac accelerator.

GA will do the 4x1.2 kW power combining experiment at 2.45 GHz with magic-tee and cavity type power combiners with the goal of geometric control algorithm development. Initial study result is also presented at this conference [7].

JLab will provide a 25-55 kW, 915 MHz magnetron transmitters, fabricate the 5-cell $Nb_3Sn$ film coated superconducting cavity at 915MHz plus 2 Fundamental Mode Power Couplers (FPCs) to be fed into GA's cryo-cooler module.

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We will integrate a 915 MHz 25kW magnetron transmitter to the conduction cooled SRF compact accelerator module for the cavity gradient demonstration at Year 3 as shown in Figs. 4 and 5.

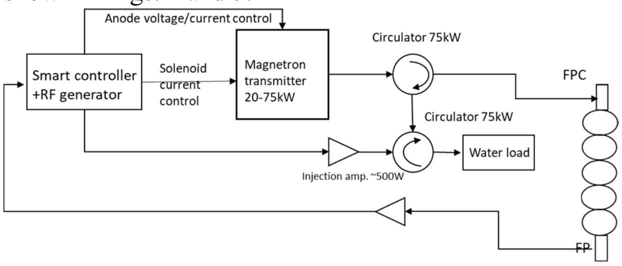


Figure 4: Top level magnetron RF control system layout for the SRF acceleration cavity gradient demonstration.

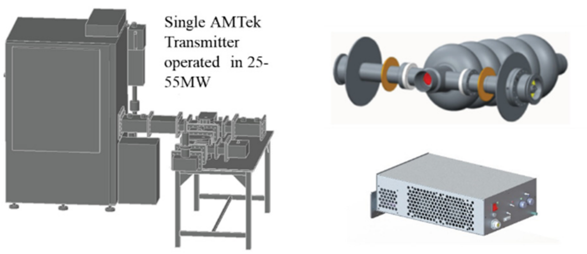


Figure 5: Single magnetron transmitter (left) to be delivered at GA and InnoSys Inc; SRF cavity and power couplers (up, right) to be built at JLab for GA's cryostat; and the first switching power supply module (down, right) built by InnoSys for the 2.45GHz magnetron systems.

## PROGRESS ON 2.45 GHz MAGNETRONS PERFORMANCE

Five modified Toshiba 2M284K, 1.2 kW, 2.45 GHz magnetron heads have been tested at JLab and sent to GA. The modification with trim-coils on the water-cooling block is shown in Fig. 6. An 888 Amp-tunes coils can trim the ferrite magnetic field in ±8.9%. All magnetron heads can be operated up to 1.2 kW power at stable ~32ºC tube temperature. Depending on the installation of ferrite magnets, the characteristic of each magnetron performs slightly differently including the I-V curves and the trimming ranges within ±2 A current. Figures 7 and 8 show their typical performance. Among them, #2 magnetron shows the best sideband noise reduction when the optimum feedback loop (from anode current pickup to trim-current modulation) gain and a bandpass filter are used. Its performance can be comparable to the klystron now in marginal difference as shown in Fig. 9.

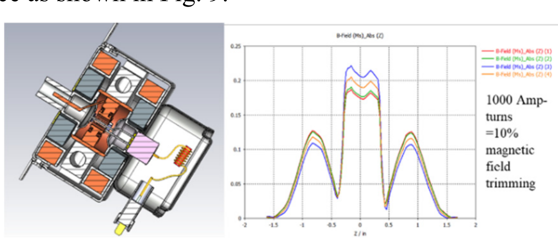


Figure 6: CST simulation model (left) and simulated trim-coil trimmed magnetic field cross the anode-cathode gap (right).

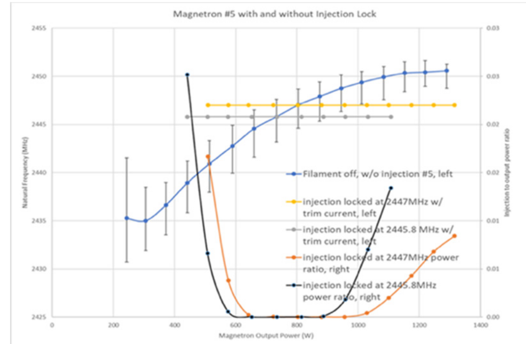


Figure 7: Using injection power (on right vertical axis) and trim-coil current to lock #5 magnetron frequency (on left vertical axis) with the trimming ranges indicated in vertical error bars) at two fixed injection frequencies to overcome the magnetron natural frequency push during the power rise (on horizontal axis).

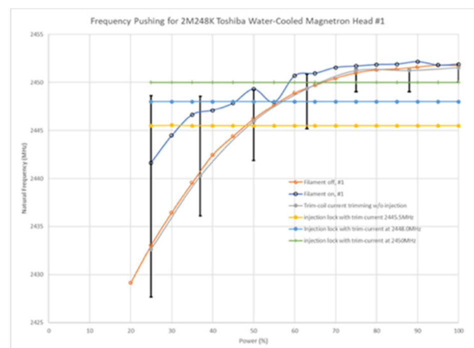


Figure 8: #1 magnetron has a larger trimming range and locking frequency band on #1 magnetron comparing than the #5's shown in Fig. 7.

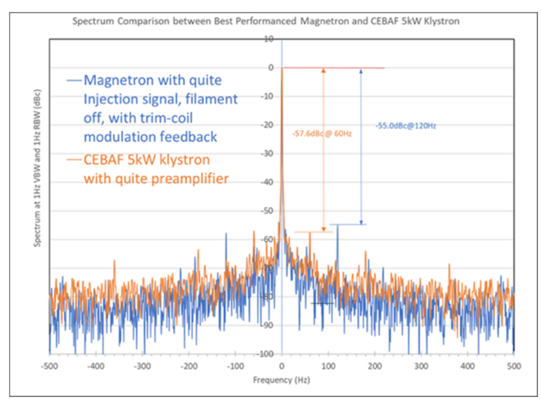


Figure 9: #2 magnetron spectrum comparing to CEBAF 5 kW klystron with their peak powers normalized at 0 dB.

## CONCLUSION

The R&D efforts on the magnetron experiments have made significant progress toward their application for the industrial compact accelerators. The performance of individual magnetron at 915 MHz has demonstrated to be ready for the beam acceleration of superconducting cavity. The non-linear fast feedback controller is next critical development for the RF amplitude and phase modulations for the magnetron driven system integration.

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