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DEMONSTRATION OF MAGNETRON AS AN ALTERNATIVE RF SOURCE FOR SRF ACCELERATORS*

Haipeng Wang#, Kevin Jordan, Robert A. Rimmer, Jefferson Lab, Newport News, VA, USA
Kyle A. Thackston, James P. Anderson, Charles. P. Moeller, General Atomics, San Diego, CA, USA
Laurence P. Sadwick, InnoSys, Inc, Salt Lake City, UT, USA

Abstract

Magnetrons have been considered as alternate high-efficiency, low-cost RF sources for linacs and storage rings for national labs and industrial applications. After the demonstration of magnetron power to drive and combine for a radio frequency cavity at 2450 MHz in CW mode, we have used trim coils adding to ferrite magnet and a water-cooled magnetron with a feedback control on coil current amplitude modulation to further suppress the sideband noise to -46.7 dBc level. We have also 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 from the 3-Phase SCRs DC power supply can be reduced to -16.2 dBc level. Further noise reduction and their power combining scheme using magic-tee and cavity type combiners for higher power application (2x50 kW) are to be demonstrated. We intent to use one power station to drive the normal conducting FPC, booster and superconducting RF cavities for the industrial linac.

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]. Comparing to traditional klystrons used in linacs and storage rings, magnetron forms electron bunches in spoke-on-hub process in circular motion in the beam-to-cavity interaction, while klystron only interacts in linear motion. The beam energy can interact with magnetron cavities in multiple circular passes than the single pass in klystron cavities. The spent energy in magnetron is reused for the cathode heating than being wasted in the beam dump of klystron. To overcome the space-charge force from de-bunching effect, the klystron designs have used lower perveances and longer structures (more cavities) to get higher efficiencies, then higher fabrication cost. Depending on frequency, commercial magnetrons have been operated at 75% to 95% of DC-to-RF efficiency [2]. At Jefferson Lab (JLab), we have first demonstrated injection phase locked magnetron operated at CW, 915 MHz, 75 kW in 2022 [3]. The first installation unit cost was about $ 1 per Watt. The magnetron tube costs is even less. Current klystrons installed at CEBAF is still at ~$ 5-8 per Watt.

Solid State Amplifiers (SSAs) are nowadays more popular in SRF applications due to their robust in semiconducting fabrication and utilization in broadcast industries, however application to accelerator is typical at lower frequency (<1.5 GHz), efficiency is around 45-55%, with the cost of $ 11-15 per watt.

The phase-locked magnetron applications to industrial and medical SRF accelerators [4] could be the first achievable RF sources [5, 6] since the performance of injection phase lock and recent smarter amplitude control progress made will be shown in following sections.

INJECTION PHASE-LOCK DEMONSTRATION OF 915MHZ MAGNETRON

After first demonstrated injection phase lock to a full power of CW 75 kW on the first installed magnetron with a -26.6 dBc injection power, as shown in Fig. 1, we have obtained side band noise reduction from -11.2 dBc to -16.2 dBc at the 360 Hz sideband noise produced by the industrial SCR rectifier type of power supply when the cathode filament current was reduced from the nominal value of 88A to 65 A [3]. Unlike a 2.45 GHz magnetron, the filament power can be complete switched off, further reduction of filament current would affect the magnetron stability performance on the frequency lock.

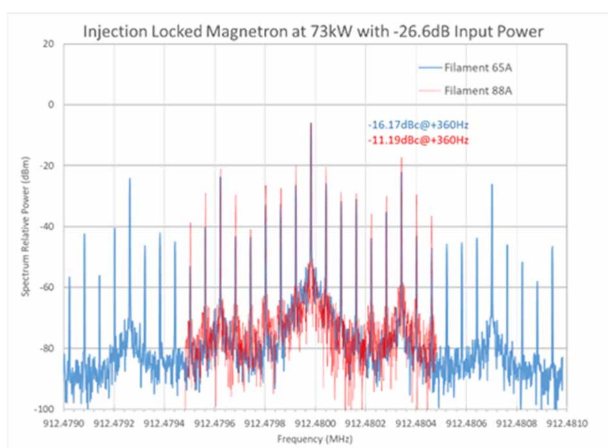

Figure 1: The Injection locked spectrums at 1 Hz of RBW and VBW to compare the noise reductions at 360 Hz on the 1st installed magnetron at 73 kW output power.

The measured anode I-V and I-E curves as shown in Fig. 2 after electrical/RF calibrations have confirmed a negative I-V slope and the DC-to-RF efficiency being

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# haipeng@jlab.org

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>90% before the injection. A calorimetry measurement is going to further confirm this efficiency.

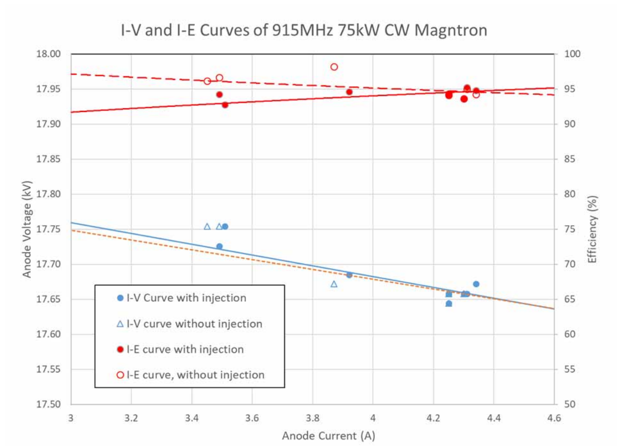

Figure 2: Measured anode voltage vs anode current (I-V) (blue, left aisle) and the DC-to-RF efficiency vs anode current (I-E) (red, right aisle) curves on the 1st magnetron unit.

In the injection phase lock scheme, two high power WR975 circulators were used. Trimming circulators' magnetic fields by small permanent magnets and shunt plates is critical for the maximization of total isolation of S12= -51.05 dB and the minimization of output port 2 reflection S22=-23.82 dB after assembling the secondary circulator. We have used the same set of circulator assembly by flipping them 180° on a nonmagnetic stainless-steel table to do the phase lock test on the second unit, also at 75 kW level. We have achieved a very similar performance of injection phase lock with reduction of the sideband noise at 360 Hz. The natural magnetron frequency has been changed from the cold on both of 918.769 MHz to hot 912.390 MHz on unit #1 and 912.601 MHz on unit #2, only 211 kHz difference at 72-73 kW power level, which is going to be relative easier for the power combining in amplitude and phase controls. Figure 3 shows the injection locked spectrums in 1 MHz bandwidth with RBW=9.1 kHz and VBW=9.1 kHz.

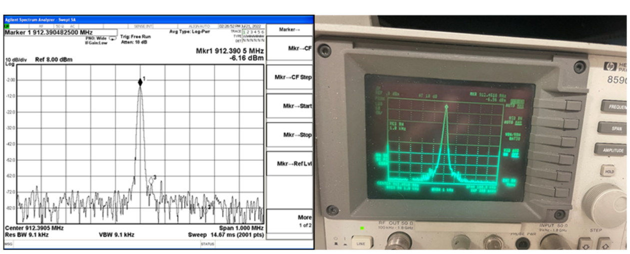

Figure 3: Injection phase-locked magnetrons, the spectrum measured on the first unit (left) on July 14, 2022, and at the second unit (right) on Dec. 16, 2022.

Further frequency push to lock at 915 MHz needs a separated control on the solenoid current or its dividing shunt resistor since the magnetron solenoid is in a series connection to the anode voltage circuit.

The stability of sub-Hz locking performance indicated 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 to control within a bandwidth of a few kHz is necessary to suppress the sideband and microphonic noises. Injection phase lock stability, locking bandwidth and speed have been studied by Adler [7] and Chen's [8] models. Our further experiments at 2.45 GHz test stand on the locking bandwidth, speed and the amplitude modulation have confirmed the proof of principle of these feasibilities.

INJECTION LOCKING BANDWIDTH AND STABILITY

The injection locking bandwidth can be expressed by the Adler [7, 8] equation:

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

Here, P_{inj} is injection power, P_{out} is output power, Q_L is the loaded Q of magnetron, ω_i is the frequency of injection signal, ω_0 is instantaneous natural frequency of magnetron, α is phase lag between electron rotating spoke and resonant rf voltage peak, called frequency pushing parameter.

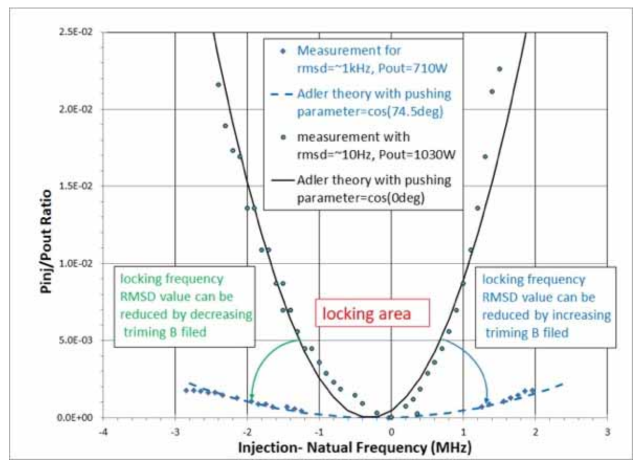

Figure 4: Injection phase locking bandwidth and magnetic field trimming offset on the locking stability.

As shown in Fig. 4, the stability diagram can be pushed or modified by an external magnetic field. The DC offset can change the magnetron naturel frequency, the AC modulation with feedback can reduce the sideband noise. A reactive loading can pull the magnetron natural frequency into unsymmetric locking width [9, 10] which could fall into unstable or more stable area with a slow beat wave. A dumping scheme is needed for a reactive cavity load or a cavity type power combiner without a protection of an output circulator. However, a magic-tee type of power combiner has an intrinsic property to guaranty the injection phase leg to each magnetron from the output port and only one set of circulators with similar measured parameters is needed on the output.

S.C. Chen [11] has modified Adler model with calculation of locking speed and stable envelop. We have also

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measured locking transient time and locking stable boundary [12, 13]. They are it in the older of agreement as shown in Fig. 5.

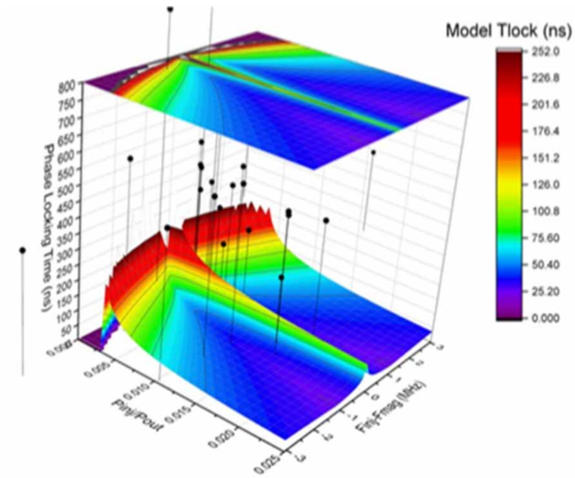

Figure 5: Measured injection locking speed against to the Chen's model prediction in 2019.

AMPLITUDE MODULATION ON PHASE-LOCKED MAGNETRON AT 2.45GHZ

To demonstrate a more effective way to reduce the frequency pushing, 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), 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 has barely made for the ±5 MHz trimming range, is about 5.63 kHz/A*turn or 14.64 µT/A*turn, typically ~10 MHz range in 20-100% power range for kitchen cooker magnetron as shown in Fig. 7.

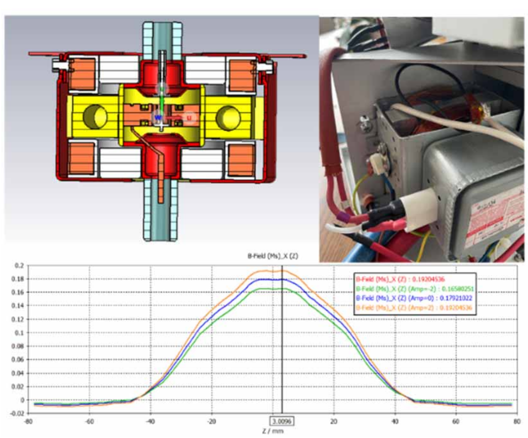

Figure 6: Trim coil modification to a water-cooled magnetron head (top-left) and installation (top-right) and the CST simulation indicating the magnetic field trimming.

However, commercial magnetron heads, even with the same model and brand, have a larger natural frequency spread more than 10 MHz as indicated in Figure 7. A pair of trim coils as shown in Figure 6 could only lock upper power range of output power (red curve).

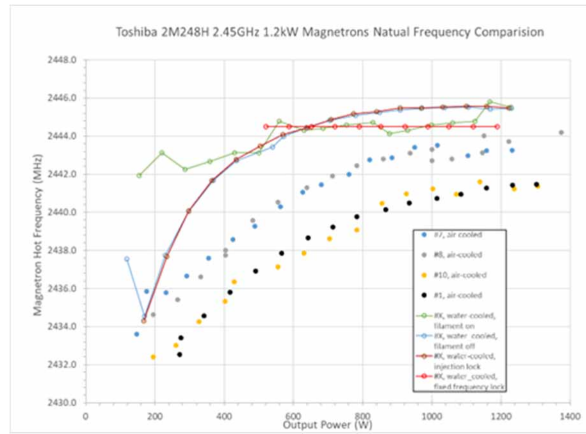

Figure 7: Magnetron natural frequency pushing range on different magnetron heads. A trim-coil modified magnetron can be injection-locked at sub-Hz frequency level in its upper power range (as shown in red-dot curve).

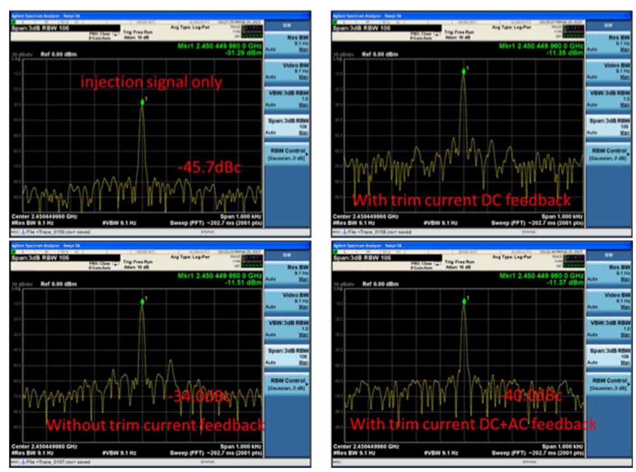

Figure 8: Recorded locked magnetron carrier and sideband frequency spectrums. The bottom-right figure is the feedback with LNA AC coupling of Gain=5, HP filter cutoff=0.3 Hz, LP filter cutoff=1 kHz.

An AC current modulation with pickup noise signal from the anode current monitor on MKS power supply, using SR 560 low noise linear preamplifier (LNA) and KEPCO BOP 50-2M bipolar power supply to the trim-coils on the amplitude modulation in kHz range can further suppress the sideband noise. After eliminating an injection noise from its 30W RF amplifier by using a "cleaner" DC power supply with <1.5e-4 rms output current ripple, we have identified the major sideband 120 Hz noise must come from the switching anode power supply. A feedback control with bandpass filter within a bandwidth of a few kHz could effectively suppress the sideband noise at 120 Hz harmonics. As shown in Figure 8, the sideband noise at 120 Hz has been reduced from -34.0 dBc to -40.0 dBc level. Carrier

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frequency peak has been increased from -11.51 dB to -11.37 dB. All other sideband noise of higher harmonics are gone.

COMPARISION WITH KLYSTRON

Comparing magnetron spectrum with active feedback with best parameters on the trim-coils, the reduced noise of 120 Hz is at -46.7 dBc level, to a typical CEBAF 5kW CPI klystron spectrum which has a lower 60 Hz sideband noise at -58.3 dBc, as shown in Fig. 8. We are developing a non-linear control algorism which 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 a magnetron operation for the SRF cavity application due to its relative narrower operating bandwidth. JLab will characterize all magnetron heads with trim coils. General Atomics (GA) will use both magic-tee and cavity type power combiners to get 4×1.2 kW output power. InnoSys, Inc. will develop the smart FPGA controlled power supplies for all magnetrons we will use at test stands.

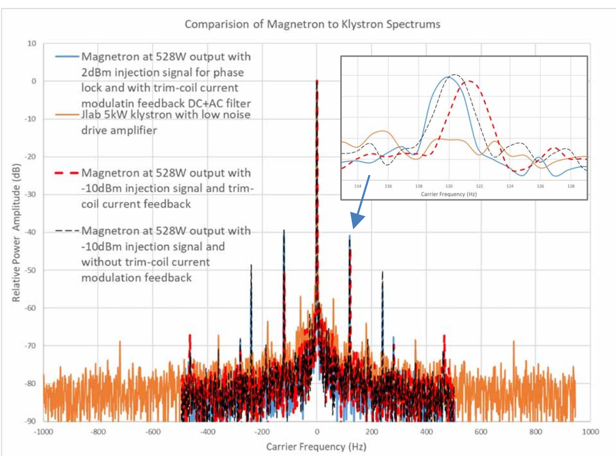

Figure 8: Noise reduction performance on the 120 Hz side band from the anode power supply by using a DC bias and AC modulation on a pair of trim-coils.

POWER COMBINING USING MAGIC-TEE FOR MW ACCELERATOR

Previous power combining experiments at 2.45 GHz by using WR340 magic-tee carried out at GA. As the result in Fig. 9 shown, nearly 100% of power combining efficiency can be achieved. However, a large natural frequency difference between two magnetron heads could cause a low combing efficiency when the water load has a finite reflection [5]. 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 (Figure 7), 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 [6-8], and the trim-coil pushing parameters have been included in this control model.

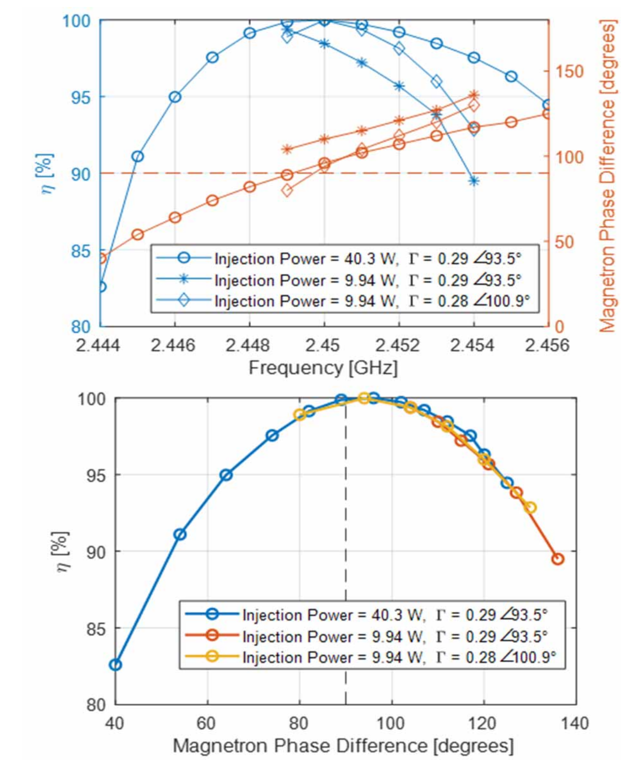

Figure 9: Top: Combining efficiency (left aisle) and magnetron phase difference (right aisle) as a function of injection frequency for different injection powers and reflection coefficients. Bottom: Combining efficiency as a function of the magnetron phase difference for different injection powers and reflection coefficients.

The peer-to-peer locking bandwidth could be further increased [14, 15]. 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 on the 915 MHz high power combing scheme as shown in Fig. 11 in our stewardship program.

At JLab, as shown in Fig. 10 in Lab 1 at LERF, two AMTek 75 kW magnetron transmitters have been installed. We are going to demonstrate 2x75 kW binary power combining by a WR975 magic-tee waveguide first, and then 4x75 kW power combining in next phase proposal. Switching power supply units with cost effective modules and smarter FPGA and PLC controllers from InnoSys will be used. Figure 11 shows the power combining layout we have proposed.

We are also going to explore the possibility of using injection coupling directly through the filament circuit without using circulators' back injection scheme [16] which is a cost saving option without second circulator. The filament lifetime increase simulations by such injection is also in the next proposal.

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Figure 10: Current magnetrons, unit #1 and #2 installed at LERF, JLab with injection locking and PLC magnetron controls.

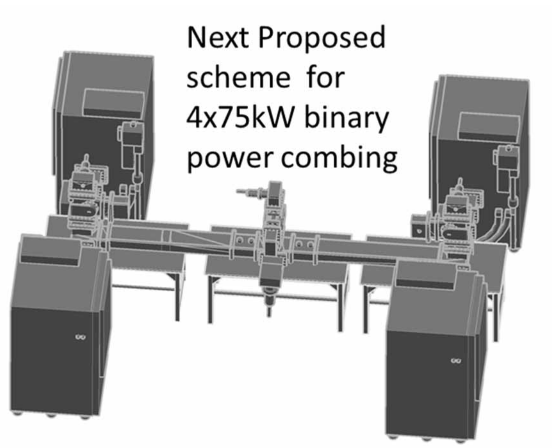

Figure 11: Proposed for 4×75 kW magnetron power combining by using WR975 waveguide magic-tees delivering power to water loads.

CONCLUSION

We have demonstrated injection phase lock performance on both 75 kW 915 MHz magnetron transmitters. Progress of injection-locked S-Band oven magnetron system without waveguide isolators is being made on the Magic-tee power combining in both system requirement and control algorithm. Trim-coil current modulation experiments with a fast feedback system at 2.45 GHz magnetron have demonstrated a good spectrum competing to a low-noise operational klystron. The 4× 75 kW high power combining is in our next experimental proposal for the industrial application in both NC and SC RF accelerator systems.

REFERENCES

[1] H. Wang *et al.*, "Use of an Injection Locked Magnetron to Drive a Superconducting RF Cavity", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper THPEB067, pp. 4026-4028. http://jacow.org/IPAC10/papers/THPEB067.pdf

[2] H. Wang, T. E. Plawski, and R. A. Rimmer, "Simulation Study Using an Injection Phase-locked Magnetron as an Alternative Source for SRF Accelerators", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3544-3547. doi:10.18429/JACoW-IPAC2015-WEPWI028

[3] H. Wang et al., "Magnetron R&D Progress for High Efficiency CW RF Sources of Industrial Accelerators", in Proc. NAPAC'22, Albuquerque, NM, USA, Aug. 2022, pp. 597-600. doi:10.18429/JACoW-NAPAC2022-WEZD3

[4] G. Ciovati *et al.*, "Design of a cw, low-energy, high power superconducting linac for environmental applications", *Phys. Rev. Accel. Beams*, vol. 21, p. 091601, 2018. doi:10.1103/PhysRevAccelBeams.21.091601

[5] H. Wang *et al.*, "Magnetron R&D for High Efficiency CW RF Sources for Industrial Accelerators", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2318-2321. doi:10.18429/JACoW-IPAC2021-TUPAB348

[6] H. Wang *et al.*, "Magnetron R&D for High Efficiency CW RF Sources of Particle Accelerators", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, p. 2233. doi:10.18429/JACoW-IPAC2019-WEXXPLS1

[7] R. Adler, "A Study of Locking Phenomena in Oscillators", in *Proc. of the IRE*, vol. 34, pp. 351-357, Jun. 1946. doi:10.1109/JRPROC.1946.229930

[8] S. C. Chen, "Growth and Frequency Pushing Effects in Magnetron Phase-Locking", MIT, Cambridge, MA, Plasma Fusion Center Note PFC/JA-89-45, Oct. 1989.

[9] G. Ziemyte, H. Wang, "Measurement and Modelling of Magnetron Injection Lock to the Stable Bandwidth", REU 2021 summer internship report, JLab-TN-21-029, 2021.

[10] H. Wang and G, Ziemyte, "Magnetron Injection Phase Stability Margin Based on Chen's Model to Extend the Asymmetric Adler Equation", Thomas Jefferson Lab, Newport News, VA, USA, Rep. JLab-TN-21-030, 2021.

[11] S. C. Chen, "Growth and Frequency Pushing Effects in Relativistic Magnetron Phase-Locking", *IEEE Trans. Plasma Sci.*, vol. 18, pp. 570 – 576, Jun. 1990. doi:10.1109/27.55928

[12] H. Wang and C. Sylvester, "Magnetron Injection Phase Locking Time and Stability Margin Calculations Based on Chen's Model", Thomas Jefferson Lab, Newport News, VA, USA, Rep. Jlab-TN-19-030, Jul. 2019.

[13] C. Sylvester and H. Wang, "Modulation and Stability Control in an Injection Locked Magnetron at 2.45 GHz", SULI Summer 2019 Student Internship Report, unpublished.

[14] C. Liu, H. Huang, Z. Liu, F. Huo, and K. Huang, "Experimental Study on Microwave Power Combining Based on Injection-Locked 15-kW S-Band Continuous-Wave Magnetrons", *IEEE Trans. Plasma Sci.*, vol. 44, p. 1291, 2016. doi:10.1109/TPS.2016.2565564

[15] X. Chen, B. Yang, N. Shinohara, and C. Liu, "A High-Efficiency Microwave Power Combining System Based on Frequency-Tuning Injection-Locked Magnetrons", *IEEE Trans. Electron Devices*, vol. 67, p. 4447, 2020. doi:10.1109/TED.2020.3013510

[16] S Wang, Y. Shen, C. Liao, J. Jong, C Liu , "A Novel Injection-Locked S-Band Oven Magnetron System without Waveguide Isolators", *IEEE Trans. Electron Devices*, vol. 70, p. 1886, 2023. doi:10.1109/TED.2023.3243041