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

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Abstract

Further theoretical and experimental studies have been performed on the magnetrons with external reactive loads either with a low-Q RF cavity or with a power combiner like the TM010 mode or Magic-tee type. The frequency pushing by a trimming magnetic field and pulling by the reflection between the magnetron and reactive load have been shown to improve the injection phase locking stability and enhance the locking bandwidth compared to the scheme to a matched load only. This principle has been further studied based on S.C. Chen's model [1, 2], equivalent circuit simulation, analytical calculation and finally compared with experimental data from the magnetron test stands at 2450 MHz.

INTRODUCTION

The scheme of using high efficiency magnetrons to drive radio frequency accelerators has been demonstrated at 915, 1497 and 2450 MHz in CW mode [3]. Since then, an AMTek 915 MHz 75 kW CW magnetron transmitter has been setup as a high power test bed at Jefferson Lab with parameters suitable for an electron linac for the environmental waste water treatment application. We have completed the electricity and cooling water hook-ups, a PLC controller upgrade, low power measurement for the magnetron tubes, circulator and the Magic-tee power combining system. Due to the pandemic restrictions at JLab, the experimental progress has been mostly made at 2450 MHz RF systems at JLab and General Atomics (GA). Further theoretical analysis of magnetron frequency pushing and pulling by injection phase lock, magnetic field trimming and a reactive load due to partial reflection on the cavity [4] and a Magic-tee as the binary power combiner [5] have also been carried out. The high power test stand, a scheme as shown in Fig. 1, including injection phase lock, amplitude control and magnetic field trimming, magic-tee power combining without using a full power circulator for industrial accelerators, has been designed for a further 2x75 kW demonstration at JLab. Its first test with single unit will be conducted in 2021 and binary power combining test will be concluded in 2022. Other applications like to build a resonator ring for a window testing facility and application to accelerator at 2450 MHz are also under consideration.

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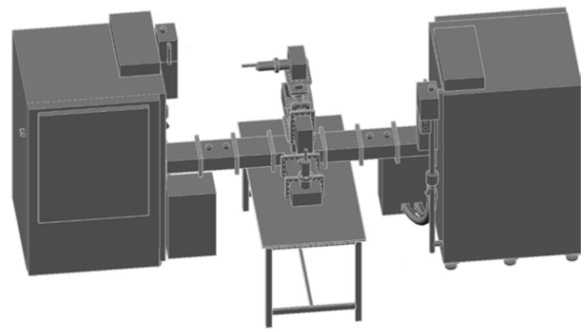

Figure 1: Two AMTek 75kW@915MHz, CW magnetron units to be power combined by a magic-tee at JLab.

LOWER POWER MEASUREMENT ON 915 MHz TUBES

The S11 Vector Analyser Network (VNA) measurement on the magnetron tube's WR975 waveguide launcher has been done after a careful TRL calibration with 30 MHz and 50 MHz bandwidths. The data fitting technique uses both S11 amplitude and phase information [6]. A MathCAD program has been developed for this data fitting [7]. An independent slot-line S22 measurement was also made with the VNA power coupled from Port 2 (N type to a WR975 top hat) to Port 1 (pick-up probes at the slot holes). The data has shown a good agreement with the TRL measurement, showing the detuned-short position is at 29.3 cm from the magnetron launcher port [8]. The measurement results are shown in Table 1 and Fig. 2.

Measurement of the "detune short" position can be used to facilitate replacement of a faulty magnetron tube in a large magnetron power combining system, with a shorting plate at the "resonance-short" position which is further $\lambda_g/2$ stub length away. Optionally using a waveguide switch at this location could allow "hot swapping" a faulty tube with the station running. This detuned-short position can be also used for the magic-tee power combiner design for the $\lambda g/4$ stub spacer.

Table1: Low Power TRL S11 Measurement Result on Amtek Magnetron Tubes

Serial #	f_{load} (MHz)	Q_{unload}	Q_{ext}	Detune-short (cm)
AM197127	918.769	1771.2	103.3	29.3
AM197111	918.769	1945.9	103.6	28.1

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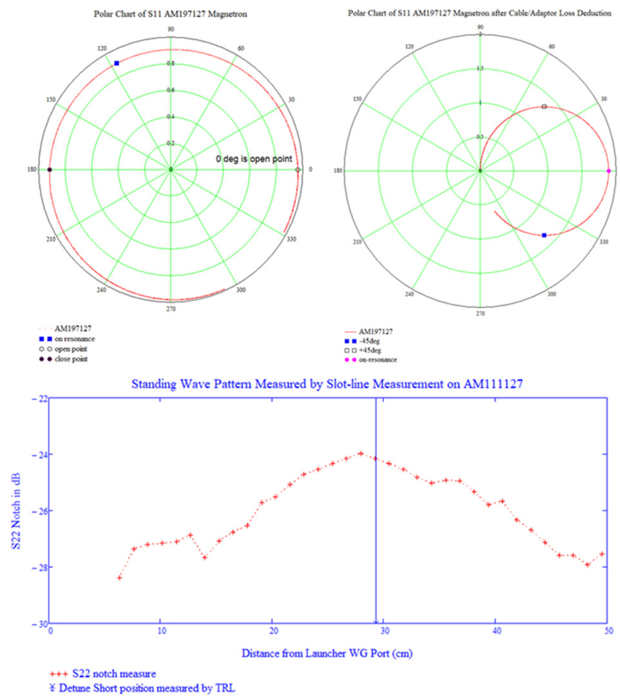

Figure 2: Top left: Raw data of S11 after TRL calibration; Top right: Data fitting after cable/adaptor loss deduction and phase rotation. Q_0 and Q_{ext} parameters are measured from this plot; Bottom: Slot-hole measurement on WR975 waveguide to confirm the TRL measurement on the "detuned short" position.

INJECTION PHASE LOCKING TIME MEASUREMENT AND CALCULATION

Injection phase locking time is an important characteristic for pulse mode operation and the power combining when two magnetrons have slightly different natural frequencies. We have used S. C. Chen's model [1, 2] to calculate the phase transient time (T_{lock}) when a single magnetron in phase lock is switched from one steady state to another. A more stable phase locking range is within 180º. A negtive slope in Chen's phase diagram can compensate the frequency pushing effect when raising the anode current. It can be achieved with aid of triming the magnetic field [9]. When the phase difference is 90º, the transient time and the injection power needed to keep within the phase locking state are minimum. When phase locking is not stable, the output phase of the magnetron goes to 360º range osccilation. The T_{lock} is determined by four basic parameters. α angle: phase lag between electron rotating spoke center and resonant RF peak voltage defined by Vaughan model [10], also called frequency pushing parameter; $\sigma = (\omega' - \omega i)/\omega 0$: relative difference of magnetron netual frequency and injection frequency to the magnetron cold frequency; μ: injection parameter $= \rho / Q_{ext} = \mathrm{sqrt}(P_{inc}/P_{ref})/Q_{ext}$, here ρ is the back injection voltage to RF output voltage ratio; $\gamma = 1/(2\omega_0)(1/Q_{ext} + 1/Q_0) = 1/(2\omega_0 Q_L)$: magnetron frequency growth rate. For the T_{lock} measurement, as shown in Fig. 3, an RF switch was used to jump between two independent injection RF sources with different frequency and phase setups. The RF switch is driven by a TTL signal in square pulse burst mode, at 25 kHz, 10 cycles in each burst. The transient states after the TTL trigger can be observed with each pulse on-off period of 4 μs as indicated in Fig. 4. The sharp rise/fall edges contains the transient T_{lock} information on the time scale of a few 100 ns. We obtained a better agreement between measurement and model prediction, as shown in Fig. 5, than previously reported [11]. A stable phase lock, a shorter locking time was obtained in the blue shade area.

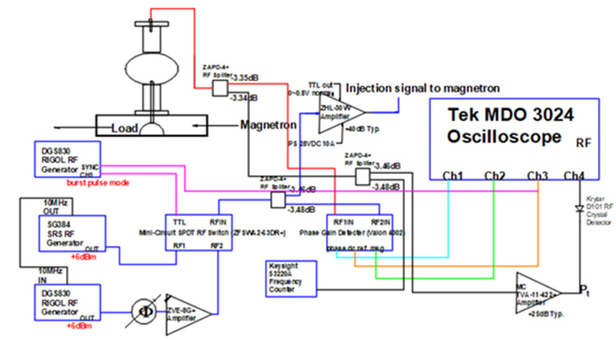

Figure 3: Experimental setup diagram using an RF switch and phase detector to measure the magnetron phase transient time from one injection lock setting to another.

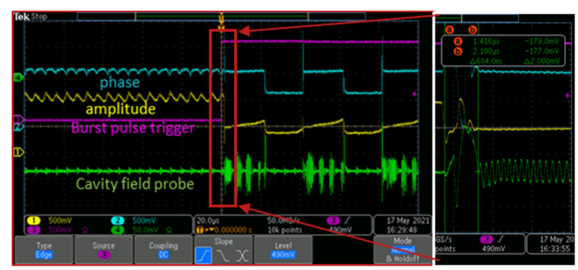

Figure 4: Blue trace on oscilloscope is the magnetron relative phase of injection to cavity's field probe, ~ 90º phase change steps on the edges can be analysed to measure the transient time T_{lock}.

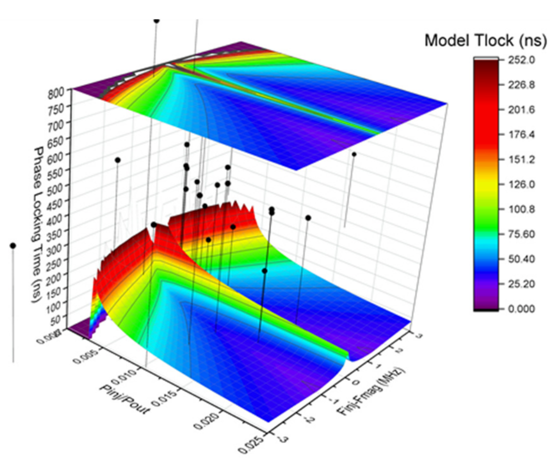

Figure 5: Phase lock time, measurement data (black dots) vs. analytical model prediction (colour contour). Its projection at the top shows the Adler equation [12]. Outside of parabolic shape (Tlock = 0) is unstable oscillation area.

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POWER COMBINING USING MAGIC-TEE AND INEJCTION

Previous binary combining systems have required high power circulators to isolate the magnetron sources, adding additional components and loss [13]. Recently, it has been shown that a modified magic-tee can be used to deliver an injection phase locking signal to two magnetrons and combine their outputs without a high power circulator. It has also demonstrated that optimal performance should occur when one magnetron source is approximately 90º out of phase from the other, hence the quarter wave extension [14]. We further explore the magic-tee combiner, demonstrating the impacts of frequency pulling and the reflections. Our system at GA combines two Toshiba 2M248h (FD) magnetrons operating at 2.45 GHz and outputting approximately 600 W each. Both magnetrons feed into WR340 sized launchers and into directional couplers. One magnetron is connected directly to a side arm of a Muegge-Gerling GA2321 WR340 waveguide magic-tee. The second magnetron is connected to a 1.7 inch (λ_g/4 at 2.45 GHz for WR340), waveguide extender before connecting to the second side arm. The injection signal is generated by an SRS SG384 signal generator and Mini-Circuits ZHL-30W-262-S+ amplifier. After being connected to a series of circulators to isolate the signal generator from reflections, the signal is input to the H-arm (sum port) of the magic-tee. The output port of the magic-tee, the E-arm (differential port), is terminated with a phase shifter connected to a water load. Keysight N1914A power meters are used to measure the forward and reflected power at each directional coupler, and a Valon Technology 4002 Phase Gain Detector is used to measure the relative phase between the magnetron outputs. Figure 6 shows a photo and diagram of the experimental setup.

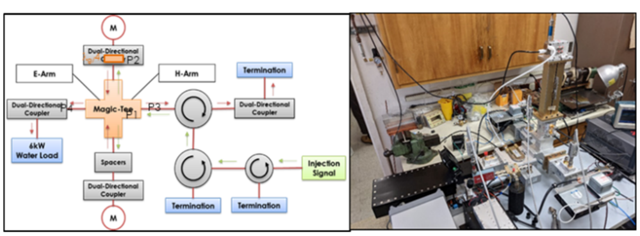

Figure 6: Left: Diagram of the magic-tee combiner system. Right: Photograph of the magic-tee combiner experimental setup.

Measurements of individual magnetrons show the natural frequencies are 2.4520 and 2.4516 GHz, respectively. Measurements of the output coupler showed 8% reflection at the load. When a 40 W, 2.450 GHz injection signal was used, the phase shifter was tuned to the optimal power combining efficiency ($\eta = P_{Eout}/[P_{Eout}+P_{Hout}]$). Because some reflection is present, 100% efficiency does not imply that all magnetron power was delivered to the output load. After tuning the phase shifter, we measured the output powers and magnetron phases across the locking bandwidth of the system. We then lowered the injection signal to 10 W, to measure a decreased locking bandwidth. Finally, we recalibrated the output phase to optimize output efficiency for the lower injection power, and collected the data again over the same locking bandwidth. These results are shown in Fig. 7.

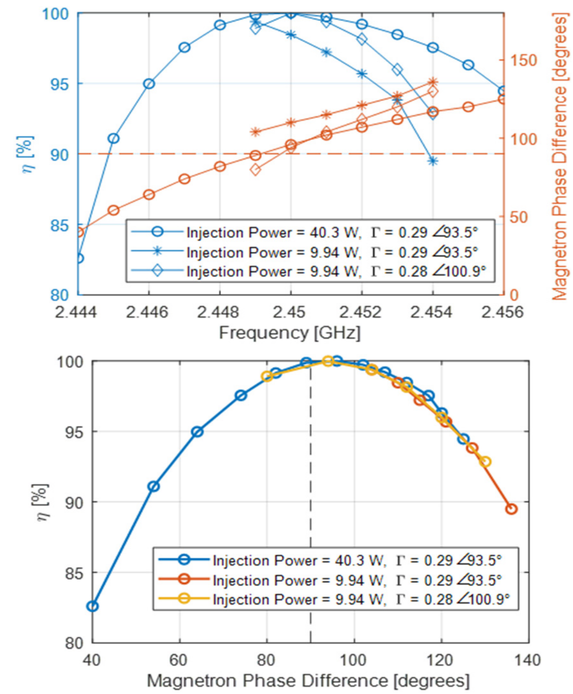

Figure 7: Top: Combining efficiency (left aisle) and magnetron phase difference (right aisle) as a function of injection frequency for different injection powers and reflection coefficients. Bottom: Combining efficiency as a function of the magnetron phase difference for different injection powers and reflection coefficients.

The 40 W injection signal indeed yielded a 12 MHz locking bandwidth, whereas the 10 W signal yielded a 6 MHz locking bandwidth. This is consistent with Adler's equations [12]. We observed for all cases, the system results in optimal efficiency when the magnetrons were about 95º out of phase. With a lower 10 W injection power the optimal injection phase was about 7º more. We have found that tuning the phase of the load reflection provides a previously un-discussed degree of freedom to optimize the combining efficiency. Our system combines effectively when the magnetrons are ~ 95º out of phase, consistent with previous work [14]. Future work will entail extending the system to combining four magnetron sources efficiently.

CONCLUSION

Using a single injection signal as phase lock reference and individual anode current as amplitude control, with the aids of trimming magnetic field and the waveguide magic-tee as magnetron power combiner, the magnetron system performance can be greatly improved, reducing overall cost and increasing efficiency of the whole RF system for industrial accelerators.

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