Experimental Study on Microwave Power Combining Based on Injection-Locked 15-kW *S*-Band Continuous-Wave Magnetrons

Changjun Liu, *Senior Member, IEEE*, Heping Huang, Zhengyu Liu, Feixiang Huo, and Kama Huang

***Abstract*— Microwave power combining based on dual 15-kW continuous-wave (CW) magnetrons in S-band is presented. The injection locking on 15-kW CW magnetrons has been successfully accomplished. The phase-locking bandwidth of each magnetron reaches 5 MHz with an improved dc power supply. Meanwhile, phase jitters are measured and analyzed briefly. The injection-locked 15-kW magnetrons have stable magnitude and tunable locked phase, which are suitable for coherent power combining. A dual-magnetron microwave power combining system has been designed and developed with an automatic phase controlling mechanism. The microwave power combining efficiency is higher than 95%. It is the first time to demonstrate a successful microwave power combining of dual 15-kW S-band CW magnetrons. The system will find industrial applications in producing diamond film from microwave plasma chemical vapor deposition. Large-power and high-efficiency microwave sources based on power combining from magnetrons are good candidates for industrial applications.**

***Index Terms*— Injection locking, magnetron, microwave power combining, phase controlling, phase-locking bandwidth.**

I. Introduction

Magnetrons find widely applications in military and civilian contexts due to their unique characteristics, such as efficient energy conversion, low cost, and high robustness. Continuous wave (CW) magnetrons have been applied to industrial applications, such as food heating and drying, material processing, and plasma deposition. However, there is a physical limitation on the power capacitance of a magnetron since the magnetron cavity size is limited by operational microwave frequency, e.g., the power capacity of a single CW magnetron is around 100 kW at 915 MHz and 20 kW at 2.45 GHz [1]. There are more and more requirements on high-power microwave in large-scale applications, e.g., in lignite coal quality improvement and plasma-enhanced chemical vapor deposition. Recently, high-power magnetron transmitters are required in superconducting linear accelerators [2], [3]. Power combining is a significant technique to meet the requirements. The low-cost and high energy conversion efficiency characteristics of magnetrons attract more and more attention of researchers.

The power combining of cook-type magnetrons has already been discussed in the microwave wireless power transmission of space solar power systems in [4]–[8]. Industrial large-power magnetrons are applied to power combining in this paper. The coherent power combining of magnetrons is difficulty to implement by the direct power combining of multimagnetrons considering the complexity of amplitude and phase characteristics of a magnetron. A free-running magnetron naturally comes with random phase and fluctuated amplitude, which may be applied to microwave heating but not to microwave coherent power combing. The injection-locking technique is powerful to lock the frequency and phase of a magnetron output. It has been studied and successfully completed on the pulse and CW magnetrons [9]–[13]. A phased array based on injection-locked magnetrons has been realized at around kilowatt level [14].

A microwave power combining system based on dual 15-kW *S*-band injection-locked magnetrons is designed, built, and measured. This experimental system aims at applications of industrial diamond film from microwave-enhanced plasma chemical vapor deposition, in which the diamond film dimension is dependent on the electromagnetic field density of microwave. The enhancement of microwave power leads to a higher atomic hydrogen concentration and a higher diamond growth rate as well [15]. Thus, high-power microwave sources are required. We use dual injection-locked 15-kW magnetrons to build the power combining system at *S*-band for the first time. The phase and amplitude stability of an injection-locked magnetron is analyzed at first. Phase tuning and automatic controlling techniques are discussed briefly then. The microwave power combining is realized by a waveguide power combiner finally. The measured power combining efficiency at the last stage is higher than 95%. It shows that high-power magnetrons are ready for coherent power combining and related industrial applications.

II. Injection-Locked Magnetron

The phenomena and theory of injection locking on magnetrons have been studied since [16] and [17]. The methods of injection locking include injection locking by external signals [18], the peer-to-peer locking [19], and the self-injection locking [20], [21], and so on. The principle of the injection locking of a magnetron has not been fully revealed until now.

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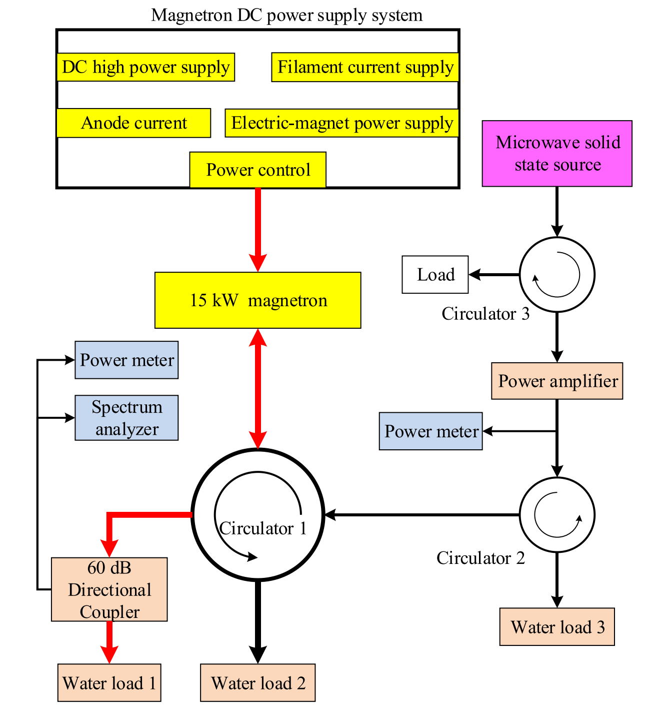

(a)

(b)

Fig. 1. (a) Schematic of the magnetron injection-locked subsystem and (b) photo of the 15-kW CK-2091 magnetron.

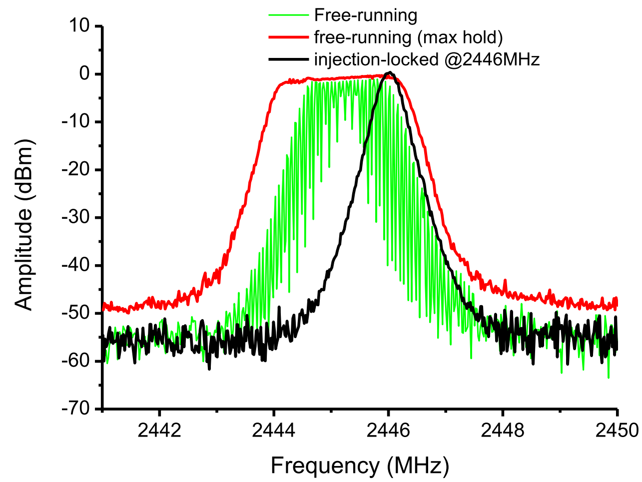

Fig. 2. Spectrum of the magnetron microwave output at various states.

The phenomenon of the injection locking of a magnetron is a free-running magnetron responding to an injected signal. After instantaneously sophisticated interaction, the phase and frequency of the output of the magnetron synchronized with the injected signal.

In our experiments, an external microwave source is introduced to lock the *S*-band magnetron. The external injected microwave power is about 20 dB less than the magnetron output power. The injected power is high enough to result in a reasonable locking bandwidth. Otherwise, dual magnetrons are hard to find an overlapping frequency for coherent power combining since each magnetron has a unique locking frequency range.

Fig. 1(a) shows the schematic of the 15-kW magnetron injection-locked subsystems. A dc power supply system supply all voltage and current required by the magnetron. The microwave system is mainly based on BJ22 (WR430) waveguides. The output microwave from the magnetron is monitored by a power meter and a spectrum analyzer through a 60-dB waveguide directional coupler. Three circulators are applied to perform the injection and protect the microwave solid state source and amplifier. The main circulator (circulator 1) is a four-port waveguide circulator. Circulators 2 and 3 are waveguide and coaxial circulators, respectively. Water-cooled waveguide loads are applied to absorb microwave power in the system.

The magnetrons are made by Nanjing Sanle Electronic Information Industry Group. Company Ltd. It is a water-cooled CW magnetron, named CK-2091, as shown in Fig. 1(b). The magnetic field of the magnetron is supplied by an extra electromagnet, which has an operating dc current of 3 A to generate a 1250 Gs magnetic field intensity. The dc power of the magnetron is supplied by a dc switching power supply with cathode voltage -11.5 kV and anode current 1.8 A. The filament current required by the magnetron is 29 A. High dc voltage, filament current, and electromagnet current are all tunable. The microwave output power of the magnetron reaches up to 15 kW at free-run status.

The injecting microwave signals are provided by two microwave solid-state sources, Hittite HMC-T2220 microwave sources, which are applied to tuning injecting signal frequency and amplitude as well. Two microwave solid-state sources are phase locked together by sharing a common reference clock. One is applied to a reference signal in phase measurement in later microwave power combining as well. The injected signals are amplified and injected into magnetrons through waveguide circulators.

The output microwave spectrum and power are monitored by a Rohde & Schwarz FSP (9–7 GHz) spectrum analyzer and a dual-channel AV2433 (10–18 GHz) microwave power meter, respectively. Fig. 2 shows the spectrums of a free-running magnetron and an injection-locked magnetron at 2446 MHz. The output spectrum of the free-running magnetron is not stable, as shown by the green line in Fig. 2. The red line in Fig. 2 demonstrates the maximum output in the free-running magnetron spectrum, which is obtained by enabling the max hold function of the spectrum analyzer for 30 s. It shows that the spectrum of the free-running magneton may shift with

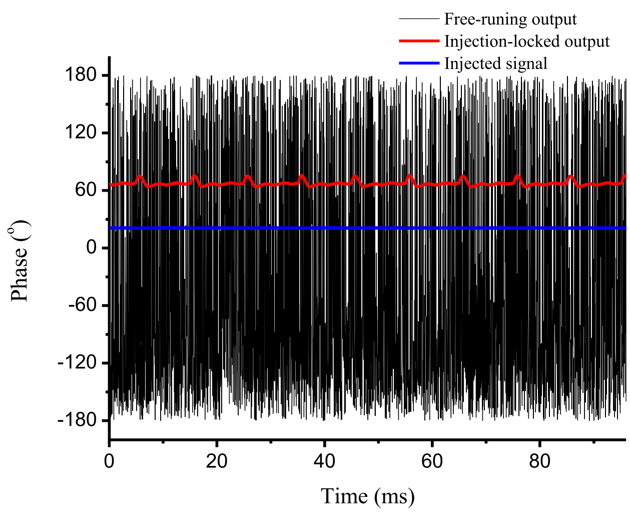

Fig. 3. Output microwave phase jitters of free-running and injection-locked magnetrons.

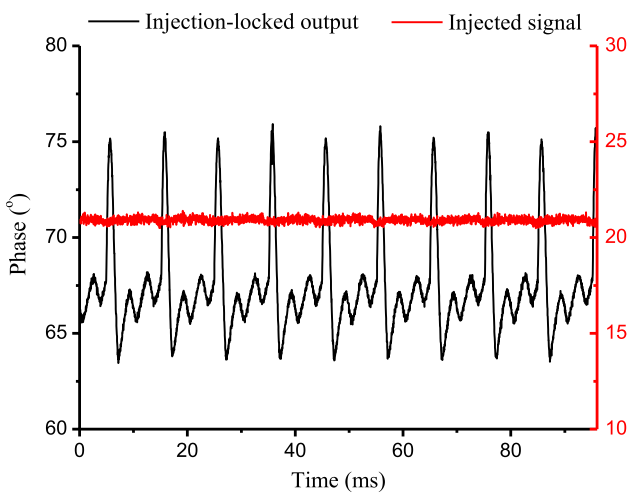

Fig. 4. Phase jitters of the injection-locked magnetron microwave output and the injected signal.

respect to time. The spectrum of a locked magnetron is shown by the black line, which is quite stable. The center frequency of the injection-locked magnetron shifts with respect to the frequency of the injection microwave signal frequency in a certain bandwidth.

An Agilent E8363C (10–40 GHz) PNA vector network analyzer is applied to monitor the phase shift between the magnetron microwave output and the reference injected microwave signal. Fig. 3 shows the measured phase shift of a free-running magnetron microwave output for about 100 ms, as shown by the black line, which is violently varying between $-180°$ and $180°$. The output microwave phase jitter of the injection-locked magnetron is shown by the red line, which shows the phase variation is limited to $\pm 6°$. The details of phase jitters of the injection-locked magnetron microwave output are shown in Fig. 4. The phase jitters of the injected signals are shown in both Figs. 3 and 4. The frequency spectrum and the phase jitters of the injection-locked magnetron show that the injection-locked magnetrons are ready for microwave power combining.

TABLE I
INJECTION LOCKING WITH VARIOUS INJECTION POWERS

Injection power (W)	Output power (kW)	Frequency range (MHz)	Lock Range (MHz)	Quality factor
35.0	13.00	2439.9~2441.9	2.0	63.4
45.0	13.00	2439.7~2442.0	2.3	62.5
55.0	13.01	2439.6~2442.1	2.5	62.4
65.0	13.00	2439.4~2442.3	2.9	59.5
75.0	13.03	2439.2~2442.5	3.3	56.1
85.0	13.02	2439.1~2442.6	3.5	56.4
95.0	13.02	2439.0~2442.6	3.6	57.9
105	13.00	2438.8~2442.8	4.0	54.9
115	13.05	2438.7~2442.9	4.2	54.6
125	13.04	2438.6~2442.9	4.3	55.6
135	13.04	2438.5~2443.0	4.5	55.2
145	13.03	2438.4~2443.1	4.7	55.0
155	13.00	2438.3~2443.2	4.9	54.5
165	13.02	2438.2~2443.2	5.0	54.5

The phase jitters of the injection-locked magnetron in current system seem to be mostly from the fluctuation or interference of the magnetron dc power supply. The period of the measured phase jitters is about 10 ms, which is coincident with the period of the full-wave rectified 50-Hz electric power supply. We will improve the magnetron dc power supply system in the future to further reduce the phase jitters of the injection-locked magnetron.

The measured results of the injection-locked magnetron are shown in Table I. The phase-locking bandwidth of the injection-locked magnetron is up to 5 MHz, whereas the injected microwave power is around 155 W. The output microwave power of an injection-locked magnetron usually is slight less than the output power of the magnetron in free-running state. Meanwhile, the insertion loss of the circulator should be taken into consideration as well. Thus, it is reasonable that the output microwave power of a 15 kW magnetron reaches only about 13∼14 kW. The injection to output power ratio is defined as

$$\rho = \sqrt{\frac{P_{\mathrm{IN}}}{P_{\mathrm{OUT}}}} = \sqrt{\frac{155\ \mathrm{W}}{13 \sim 14\ \mathrm{kW}}} \approx 0.11. \quad (1)$$

The injection power ratio is around 0.11 and a 5-MHz locking bandwidth is achieved. The locking bandwidth is not only related to the injection power but also affected by the stability of the magnetron dc power supply. The higher the ripple of the dc power supply is, the narrower the locking bandwidth is. The voltage ripple of the dc power supply in our current system is less than 1.5%.

The Adler equation [22], [23] shows the relation between the locking bandwidth and injection power of a magnetron as

$$|\omega_i - \omega_0| \approx \frac{\mathrm{BW}}{2} \leq \frac{\omega_0 \rho}{2Q_{\mathrm{ext}}} \quad (2)$$

where ω_i is the injection angle frequency, ω_0 is the free-running angle frequency of the magnetron, BW is the magnetron locking range, and Q_{ext} is the quality factor of the external load. Thus, we varied the injection microwave power from 35 to 165 W and measured the locking frequency range of the magnetron. Then we applied (2) to estimate the magnetron quality factor of the external load. The measured

TABLE II
INJECTION-LOCKED MAGNETRON

Injection-locked magnetron	No. 1	No. 2
Injected power (W)	155	157
Output power (KW)	13.0	13.9
Phase-locking range (MHz)	2438.3~2443.2	2441.7~2446.8
Overlapping frequency (MHz)	2441.7~2443.2	

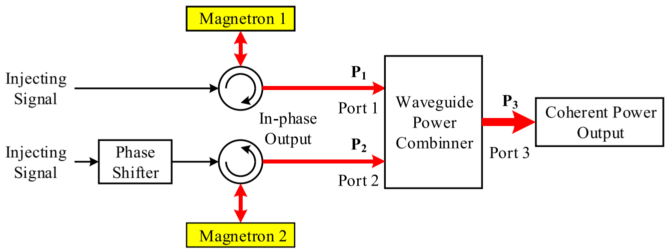

Fig. 5. Principle diagram of dual injection-locked magnetrons applied to microwave power combining.

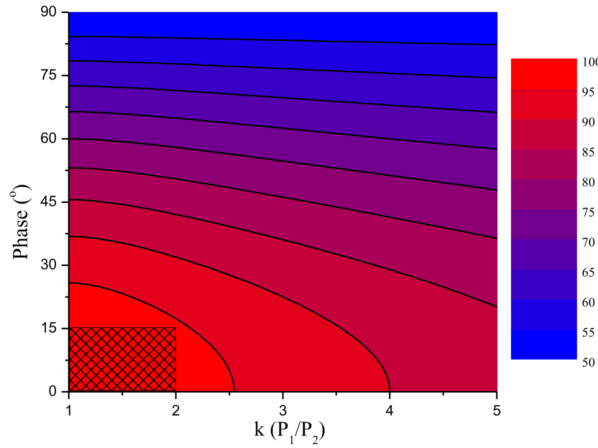

Fig. 6. Power combining efficiency with respect to input power ratio and phase difference.

results are shown in Table I. We finally estimate the magnetron quality factor of the external load is 57.5 through linear fitting.

The output powers of the dual magnetrons are 13.0 and 13.9 kW, respectively, whereas the injection power is 155 W, as shown in Table II. The overlapping frequency range of the two injection-locked magnetrons is from 2441.7 to 2443.2 MHz, which has a 1.5-MHz bandwidth. Thus, microwave power combining will be performed in this frequency range.

III. Coherent Power Combining Experiments

Dual injection-locked magnetrons have an overlapping frequency range for coherent power combining. The principle diagram of the power combining system is shown in Fig. 5. We tune the dual magnetrons to the same frequency by injecting coherent microwave signals at f_0. The phase shift of magnetron 2 is controlled by a phase shifter, which is located before the solid state power amplifier. A low-power coaxial phase shifter with a controlling interface is enough to perform the phase shifting on the injection microwave. The microwave powers P_1 and P_2 from the dual magnetrons are tuned to be in phase for power combining. A three-port waveguide 3-dB combiner is applied to combine P_1 and P_2, in which the output power is P_3.

Assuming the waveguide power combiner is a lossless 3-dB three-port power combiner with perfect impedance matching at the output port, which is port 3 in Fig. 5 and the power combing output port, its scattering matrix is

$$[S] = \begin{bmatrix} 1/2 & -1/2 & -j/\sqrt{2} \\ -1/2 & 1/2 & -j/\sqrt{2} \\ -j/\sqrt{2} & -j/\sqrt{2} & 0 \end{bmatrix}. \quad (3)$$

In the power combining based on the 3-dB power combiner, while the input microwave powers are P_1 and P_2 with a phase difference θ, the output power P_3 is

$$P_3 = \frac{P_1 + P_2}{2} + \sqrt{P_1 P_2}\cos\theta. \quad (4)$$

The power combing efficiency is defined as

$$\eta = \frac{P_3}{P_1 + P_2} = \frac{1}{2} + \frac{\sqrt{k}\cos\theta}{1+k} \quad (5)$$

where k is the input power ratio P_1/P_2.

Fig. 6 shows the simulated power combining efficiency with respect to input power ratio k and phase difference θ. It shows that the power combining efficiency is sensitive to the phase difference. If we set the power combining efficiency goal to be 95%, the power ratio and phase difference ranges are obtained from (5). A quick estimation has been done in Fig. 6, e.g., in the shadowed region, $1 < k < 2$ and $\theta < 15°$ guarantee that the power combining efficiency is higher than 95%. The experiments of magnetron phase locking show that the designed injection locking system may satisfy the requirements.

In the power combining experiment system, dual 15-kW injection-locked CW magnetrons are locked to 2442.0 MHz, which is in the overlapping frequency range of the magnetrons. In the experiments, the phases of magnetrons do not keep locking to the injection microwave and shift slowly with respect to time, which seems to be due to the magnetron temperature variation, dc voltage drift, filament current variation, and so on. The power combining efficiency decreases, if no automatic phase compensation is performed. Thus, an automatic microwave phase shifting mechanism is applied by monitoring the output microwave phase difference and tuning the injection microwave phase.

The schematic of the microwave power combining system based on dual injection-locked 15-kW CW magnetrons is shown in Fig. 7. The red arrowed line indicates the power supply to the magnetrons and paths of large-power microwave. Two independent magnetron dc power supplies are used to the two magnetrons, respectively. The cathode voltages and filament currents are able to be adjusted independently. The purple arrowed lines connect the microwave source, power amplifier, and circulators, which are the main components of microwave injection-locking branch. The green arrowed lines connect directional couplers, phase/gain detector, phase shifter, and computer, which are the phase controlling branch

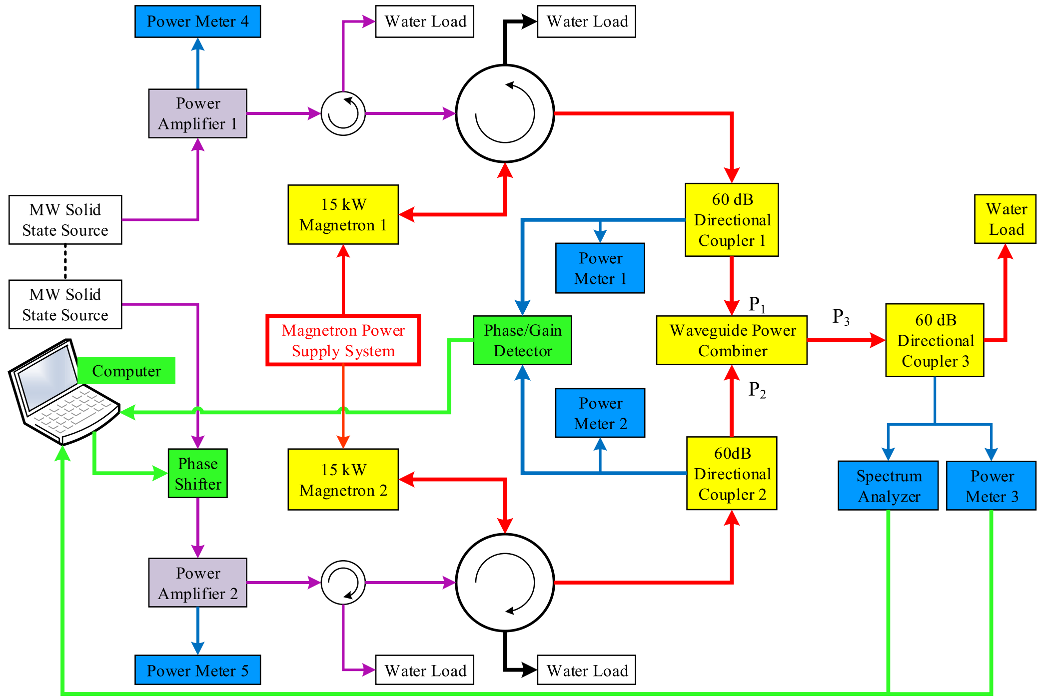

Fig. 7. Schematic of the microwave power combining system based on two-way injection-locked 15-kW CW magnetrons.

of the microwave power combining system. Two 60-dB directional couplers 1 and 2 are applied to measure the output powers P_1 and P_2 of the dual magnetrons, which are the input powers of the power combiner as well. Another 60-dB directional coupler 3 is applied to measure the microwave power combining output. A spectrum analyzer is connected here as well to monitor the process of injection locking and power combining. Two four-port circulators are applied to protect the magnetrons and isolate the injecting microwave and large-power microwave from magnetrons. An H-plane waveguide tee power combiner is applied to combine microwave powers P_1 and P_2 from the dual magnetrons. The phase/gain detector is designed with a megawatt (MW)/IF gain/phase detector MMIC chip AD8302. It provides an accurate measurement on phase difference over a 0°–180° range and has an output voltage scaled to 10 mV/°. A Telemakus TEP4000-5 digital USB phase shifter is applied to tune the output microwave phase of magnetron 2. The digital phase shifter has a minimum phase adjusting range of 360° (400° typical) with 12-b, 0.25° resolution.

The controlling subsystem is a key part of the power combining system. It is applied to monitorthe incident and reflected powers, the phase difference between the dual magnetron outputs, and magnetron voltage and current and temperatures, and tune the phase shifter to keep the highest combining efficiency. Once high reflection, abnormal voltage/current, and high temperature are found, the controlling system will shut down the dc power supply to protect the system. The safety guarding process is running over the whole experiments and sends warnings messages to the controlling interface. If there is any trigger safety indicators exceeding the limits, the process will shut down the power supply of the whole system.

The phase controlling process obtains the phase difference between to dual magnetrons and the total output microwave power. We have written a LabWindows/CVI program for data collecting and phase tuning. The phase controlling process includes two tuning methods: a fast tuning and a slow tuning.

1) The fast tuning is mainly based on the phase difference data. Once the maximum output microwave power P_3 has been reached through tuning the phase difference between dual magnetrons, the phase difference $\theta_{\max}$ is recorded. Then, the phase shifter is automatically tuned to keep the phase difference to be $\theta_{\max}$. The data acquisition and phase shifting time is on the order of 10 ms.
2) The slow tuning is based on the output power data. Once the system finds the output power P_3 drops, the phase difference $\theta_{\max}$ is recalibrated. A new $\theta_{\max}$ is updated. The fast tuning will use the updated $\theta_{\max}$ as its goal. The slow tuning is usually triggered on the order of dozens of seconds.

The facilitated phase controlling flow chart is shown in Fig. 8, where k is a coefficient to determine the power drop to trigger a tuning on the maximum output power. We have set it to 0.95 in our experiments.

In the power combining experiment, the dual magnetrons are locked at 2442.0 MHz by coherent injecting microwave signals. The microwave power combining system is designed and built. The hardware system is shown in Fig. 9. The water-cooling system is connected to magnetrons, circulators, and water loads. Another cooling tank and a cooling tower are not shown in Fig. 9.

Table III shows the experimental results of the microwave power combining based on dual injection-locked 15-kW CW

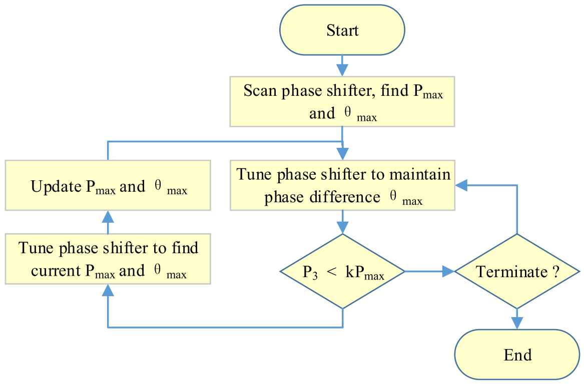

Fig. 8. Program flowchart of phase controlling.

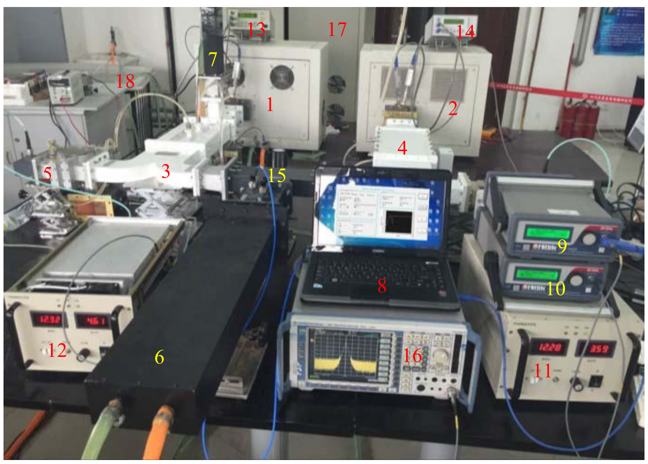

Fig. 9. Power combining system (1 and 2: the magnetrons with electromagnets, 3–5: circulators, 6 and 7: water loads, 8: laptop, 9 and 10: microwave solid-state sources, 11 and 12: microwave power amplifiers, 13 and 14: microwave power meters, 15: waveguide tee combiner, 16: spectrum analyzer, 17: magnetron dc power supply, and 18: water tank).

TABLE III
POWER COMBINING EFFICIENCY

No.	P_1 (kW)	P_2 (kW)	P_3 (kW)	Combining Efficiency
1	12.9	13.7	25.6	96.2%
2	13.1	14.1	26.2	96.3%
3	13.0	13.9	25.8	95.9%
4	13.1	14.1	26.3	96.6%
5	12.7	13.7	25.4	96.2%
Average	13.0	13.9	25.9	96.2%

magnetrons. The output microwave power is measured by a power meter through a waveguide directional coupler. The output microwave power reaches 25–26 kW. The power combining efficiency is higher than 95%. The average power combining efficiency reaches 96.2%.

IV. CONCLUSION

The coherent power combining experimental system of dual injection-locked 15-kW *S*-band magnetrons has been designed, built, and measured. The injection-locking bandwidth reaches 5 MHz with 155-W injection microwave power, and the output phase jitters of injection locked magnetron are less than $\pm 6^\circ$. It shows that the Adler equation seems to be still a valid approach to reveal the relation between injection-locking bandwidth and injection power of a large-power magnetron. The estimated magnetron quality factor of the external load is 57.5 ± 2.5. The phase difference between two magnetrons is tuned through a digital phase shifter to reach a high-power combining efficiency. A LabWindows/CVI controlling interface is designed, and the automatic phase tuning is realized by monitoring the output microwave phase difference of magnetrons and the combining output microwave power. The total output microwave power is 25.9 kW and the average power combining efficiency is 96.2%.

It is the first time that the microwave coherent power combining of dual 15-kW *S*-band CW injection-locked magnetrons has been presented. The injection locking and phase tuning make large-power magnetrons ready for coherent power combining. An automatic phase controlling mechanism guarantees the power combining efficiency. We will go on studying coherent power combining of four injection locked magnetrons and apply the microwave source to industrial applications, e.g., microwave enhanced plasma chemical vapor deposition. We believe that large-power and high-efficiency microwave power sources based on coherent power combining from magnetrons are good candidates for industrial applications.

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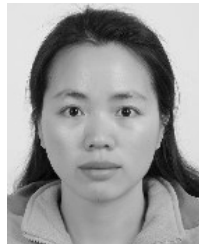

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