FERMILAB-CONF-13-314-AD-TD

HIGH-POWER MAGNETRON RF SOURCE FOR SUPERCONDUCTING LINACS OF ADS AND INTENSITY-FRONTIER PROJECTS*

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Abstract

A high-power magnetron RF source with a rapid control in phase and power based on injection-locked CW magnetrons is proposed to drive individually Superconducting RF (SRF) cavities with an energy gain of ≈20 MeV/m for proton or ion GeV-scale linacs of the Accelerator Driven Systems (ADS) or other intensity frontier projects. The RF power up to few hundreds kW is required for the SRF cavity accelerating an average beam current of 10 mA or more. Experimental tests performed with 1 kW magnetrons operating in injection-locked mode indicate the potential capability of the proposed RF source to power the SRF cavities with instability of the accelerating field phase and amplitude of less than 1 degree and 1%, respectively, utilizing a phase control. The controlled RF source will suppress parasitic modulation of the accelerating field in the SRF cavities caused by mechanical oscillations, perturbations resulting from beam loading, dynamic detuning, ripples resulted from the power supplies of the magnetrons, etc. Utilization of the magnetron RF sources will significantly reduce capital cost of the superconducting linacs over the traditional RF sources as klystrons, IOTs and solid-state amplifiers. Results of the performed experimental tests and the evaluations are analysed and discussed in this report.

INTRODUCTION

Intensity-frontier GeV-scale accelerators for proton or ion beams are crucial for ADS and other state of the art projects. One of general requirements for such accelerators of non-relativistic or weakly relativistic particles is a small beam emittance. For an RF system to satisfy this requirement, it has to provide optimal phase and amplitude in each individual SRF cavity, [1], and has to be able to suppress all perturbations of the accelerating field in the cavities. The perturbations in the SRF cavities resulting from mechanical oscillation (the “microphonics” and the oscillations caused by Lorentz-force) can be suppressed by the damping techniques based on a control of the amplitude of the accelerating field, [2, 3]. Additional perturbations of the accelerating field in SRF cavities caused by the dynamic tuning errors and the beam loading can be suppressed by a control of the phase of the accelerating field.

*Work was supported by the US DOE grant DE-SC0006261 and Muons, Inc.-Fermilab collaboration

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Using traditional RF sources such as klystrons, IOTs and solid-state amplifiers to individually feed the SRF cavities with individual amplitude and phase control significantly increases the capital cost of the linac projects. Utilization of MW-scale CW klystrons to power groups of the cavities can lower costs, but it only allows a control of the vector sum of the accelerating voltage in the group. Accelerating voltage vector sum control has not been tested for driving SRF cavities for non-relativistic or weakly relativistic particles; it may cause emittance growth, leading to beam losses because of non-optimized values of phase and amplitude of the field in individual SRF cavities.

The CW magnetrons are efficient and less expensive than the aforementioned RF sources, [4], thus utilization of the magnetron RF sources in intensity-frontier linac projects will significantly reduce the capital cost.

Analysis of the transient processes in a 2.5 MW magnetron, locked by a frequency (phase)-modulated signal, and modelling of the process, considering the magnetron as a forced oscillator, [5-7], demonstrated that the frequency (phase) response of the injection-locked magnetron on the controlled locking signal is quite linear, has small phase error and quite wide bandwidth, [8].

The experiments with 1 kW, CW magnetrons, injection-locked by a phase-modulated signal as described in this paper, indicate that the phase perturbations inherent in the magnetrons (phase pushing caused by ripples of magnetron power supplies, an influence of the magnetron AC filament circuitry) as well as the perturbations of the accelerating field in the SRF cavities can be suppressed by a fast phase control.

Thus the injection-locked magnetrons are capable of being phase-controlled to satisfy the requirements to feed the SRF cavities for ADS and intensity-frontier linacs.

Results of the study and experimental tests of the RF source performed with 1 kW CW magnetrons are presented and discussed in this work.

THE MAGNETRON RF SOURCE WITH A PHASE AND POWER CONTROL

The concept of the magnetron high-power RF source utilizing fast phase and power control is shown in Figure 1, [9]. The transmitter consists of two identical channels (A and B) of cascaded injection-locked magnetrons, combined in power by a 3-dB hybrid. For phase management, the phases at the inputs of both the cascaded magnetrons are controlled simultaneously and equally, while the power management is provided by a control of

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

the phase difference at the inputs of the two channels. The 2-cascade injection-locked magnetron system includes a low-power magnetron to reduce the required locking power for the high-power RF source. It allows a locking power approximately -30 dB that of the output power of the RF source. This transmitter configuration allows for the wideband phase and power control.

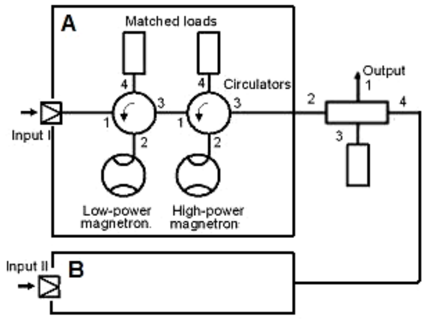

Figure 1: Block-diagram of the high-power magnetron RF source rapidly controlled in phase and power.

EXPERIMENTAL APPARATUS

All active components of the transmitter setup have been tested experimentally using two 1 kW CW, microwave oven magnetrons with a difference in free running frequencies of < 6 MHz. This allowed operation with both magnetrons locked at the same frequency (2.469 GHz). The experiments were performed in pulsed mode with pulse duration of 5-15 ms at low repetition rate (0.25 Hz). This allowed using low average power RF and High Voltage (HV) components. Operation in the pulsed mode also allowed testing applicability of the CW magnetron RF source for pulsed linacs. Both magnetrons, which have dissimilar Volt-Amps characteristics, were powered by a single modulator using the partial discharge of a 200 μF charging capacitor. A compensated divider was used to power the magnetron with lower anode voltage when both magnetrons operated simultaneously.

The level of ripple seen by the magnetrons was negligible in the modulator, however, the capacitor introduced a voltage droop of ≈ 0.4% to the 5 ms pulse when the modulator was loaded by the two 1 kW magnetrons. The wavefront of the pulse feeding the magnetrons did not exceed 0.8 μs. Shapes of the voltages and currents of both injection-locked magnetrons are shown in Figure 2.

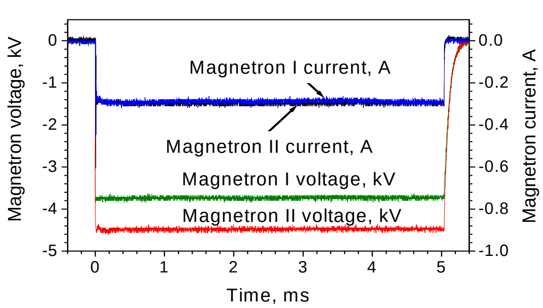

Figure: 2. Traces of currents and voltages of magnetrons operating simultaneously in injection-locked mode.

All experiments described in the presented work were conducted at nominal magnetron filament voltage.

The magnetrons were installed in two separate modules, [8], allowing commutation of inputs and outputs. It was verified that each CW magnetron operating in pulsed regime was injection-locked, being pre-excited by a CW TWT amplifier driven by a CW signal generator N5181A as it is shown in Fig. 3, [ibid.].

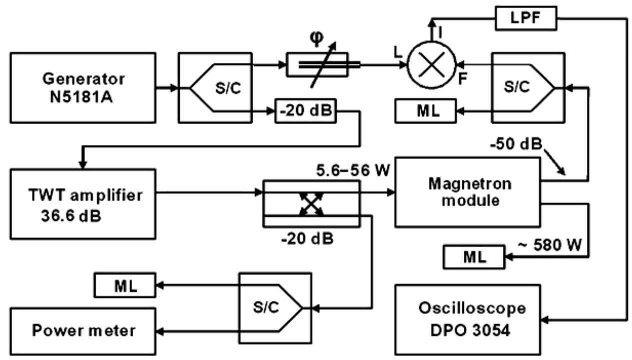

Figure 3: Experimental setup to test and study operation of magnetrons in injection-locked mode. S/C is a 3-dB splitter/combiner; ML is a matched load.

The intrapulse phase variations of the injection-locked magnetrons were measured using a phase detector including a phase shifter, φ, a double balanced mixer and a Low Pass Filter (LPF). For the measurements, triggering of the modulator was shifted by 1 ms relative to the zero crossing of the magnetron filament current. The magnetron filament circuitry elements were screened to reduce the magnetic fields affecting the magnetron phase instability. The phase shift and the screening resulted in significant decreasing the phase instability of the injection-locked magnetrons compared with earlier measurements, [8].

The measured phase variation of one of the magnetrons is plotted in Figure 4.

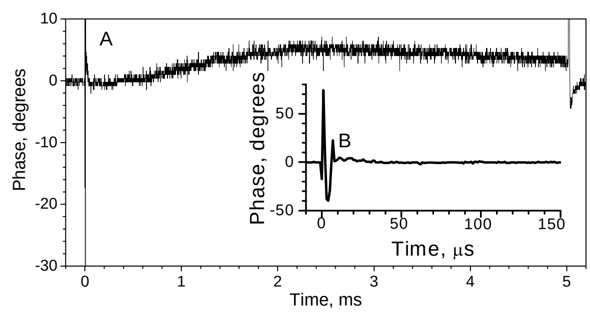

Figure 4: A- phase variation of the injection-locked CW magnetron operating at locking power of -9.6 dB, and a pulse duration of 5 ms. Inset B shows the phase variation zoomed in time.

The traces A and B in Figure 4 show phase variations of the injection-locked magnetron operating in pulsed mode. The variations are composed of a low frequency (less than few kHz) and a high-frequency (more than few tens of kHz) components, respectively.

The low-frequency components are regular and stable from pulse-to-pulse. They are phase perturbations resulting from transient processes in the injection-locked magnetron. The measurements of phase variations of the TWT amplifier driving the magnetrons did not show the low-frequency components.

The high-frequency phase noise magnitude was measured to be < 0.4 degrees (rms) in the main part of the pulse (t ≥50 µs), reflecting the contribution of the CW TWT wide-band amplifier.

Notable phase variation at the leading edge of the modulator pulse during the first ≈ 10 µs, Figure 4B, may result from phase pushing caused by several phenomena: multipactoring in the magnetron cavity when the pulsed high voltage is applied and/or variation of emitting properties of the magnetron cathode caused by cleaning of the emitting surface by back-streaming electrons. The time scales for both processes match the measured phase variation time. Operation of an SRF cavity would not suffer from the measured phase variation due to large filling time (a few ms) for the cavity.

The traces plotted in Fig. 4 show a phase instability magnitude of $\Delta\varphi \leq 5.3$ degrees (peak-to-peak at t ≥ 50 µs) measured at the locking power of -9.6 dB. A decrease of the locking power increases the phase instability. The slow phase perturbations one explains by phase pushing, resulting from competing processes: an increase of the magnetron current, because of overheating of the cathode surface caused by bombardment by back-streaming electrons and a decrease of the magnetron current associated with a droop of the magnetron voltage because of the discharge of the modulator storage capacitor. The latter process dominates in the second half of the pulse.

The thermal distortion of the magnetron geometry during pulsed operation and a magnetic field, induced by the magnetron filament AC circuitry also affect the phase instability, [10]. The latter is shown in Figure 5, in plot of the perturbations magnitude, (peak-to-peak), vs. the time shift $\Delta\tau$ between zero crossing of the AC voltage and triggering of the modulator.

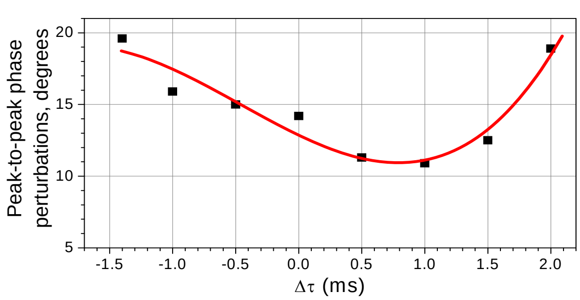

Figure. 5: Phase variations (peak-to-peak) of the injection-locked magnetron measured at locking power of -15.8 dB vs. the time shift $\Delta\tau$.

STUDY OF 2-CASCADE INJECTION-LOCKED MAGNETRON

The operation of 2-cascade injection-locked magnetron was studied with a setup shown in Figure 6, [10]. In this setup the first magnetron was injection-locked by the CW TWT amplifier. The second magnetron was locked by an attenuated pulsed output signal from the first magnetron.

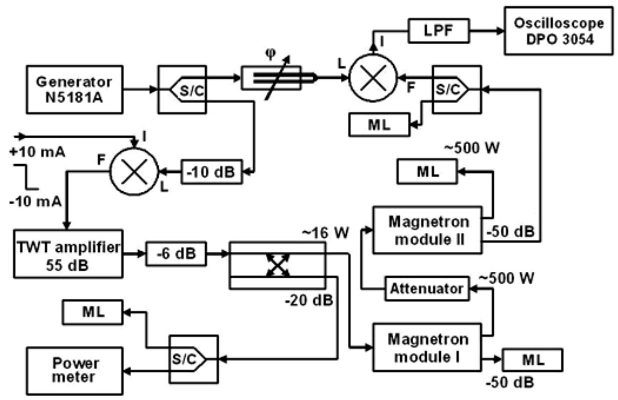

Figure 6: Experimental setup to measure phase variation of the 2-cascade injection-locked magnetron.

Measured phase instability of the 2-cascade magnetron with an attenuation value of 15 dB is shown in Figure 7.

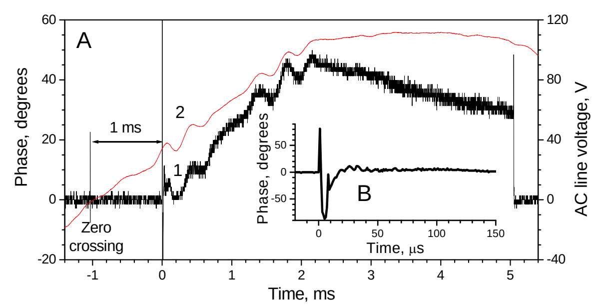

Figure 7: A- phase variations of the 2-cascade injection-locked magnetron measured at an attenuation value of 15 dB, trace 1, left vertical scale. Trace 2 is voltage in the AC line, right vertical scale. B shows a zoomed trace 1.

The plotted phase variation of the 2-cascade injection-locked magnetron, trace 1, resembles traces of the injection-locked single magnetrons, but the magnitude of the phase variation is larger because the second magnetron is locked by a phase modulated signal. Nevertheless, the plotted trace 1 clearly demonstrates that the 2-cascade magnetron was still operating in injection-locked mode. This demonstrates proof-of principle for a 2-cascade injection-locked magnetron. Faster droop of the phase trace at t ≥2.5 ms is caused by the phase pushing resulting from increased discharge of the modulator capacitor when loaded by two magnetrons.

A synchronism in the phase perturbations of the 2-cascade injection-locked magnetron with distortions of the AC line voltage, indicates that the perturbations of the magnetron magnetic field resulting from the magnetron filament circuitry, are significant even with the time optimized triggering of the modulator, Figures 5, 7.

The high-frequency noise was measured to be ≤ 0.7 degrees (rms) at t ≥50 µs at an output power of ≈ 500 W. The measured phase (trace 1 of Figure 7) demonstrates operation of the experimental setup of the 2-cascade injection-locked magnetron at a ratio of the output power to the locking power of ≈30 dB

The measured response of the injection-locked 2-cascade magnetron for a fast 180 degrees phase flip accomplished with a pulse generator and double balanced mixer on the TWT amplifier input, Figure 6, demonstrated wide bandwidth in the phase response, Figure 8, [10].

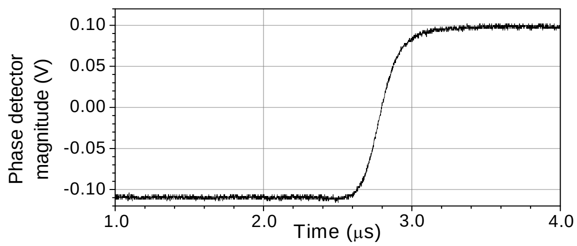

FIG. 8: Response of the frequency-locked 2-cascade magnetron on the 180 degrees phase flip measured at ratio of the output power to locking power ≈27 dB; the phase detector calibration is ≈ 0.8 degrees/mV.

A POWER CONTROL OF INJECTION-LOCKED COMBINED MAGNETRONS

The fast power control of the injection-locked magnetron utilizing power combining first was realized in the setup shown in Figure 9.

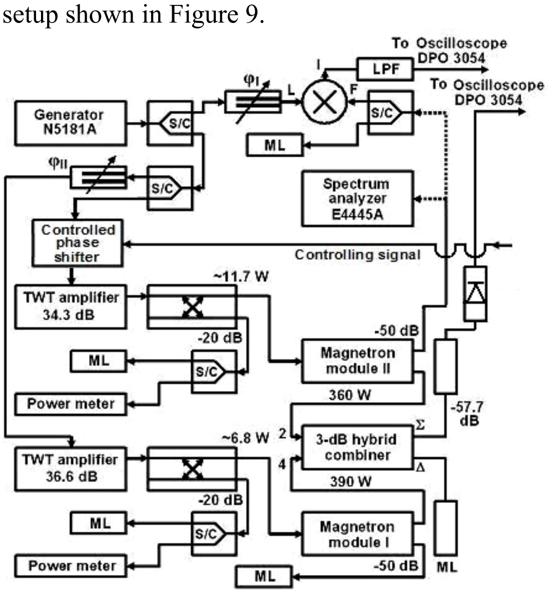

Figure 9: Setup with the injection-locked magnetrons for test of the power control by power combining.

The power control is provided by vector summation of output signals of the injection-locked magnetrons controlled by phase difference. Results of the power combining versus the phase difference caused by varying of the phase through the trombone φ_{II}, or by a controlled analogue phase shifter JSPHS-2484 (control in static and dynamic regimes, respectively) are plotted in Figure 10. The dynamic regime was realized by controlling the analogue shifter with a sequence of meander-like pulses with period of ≈30 μs.

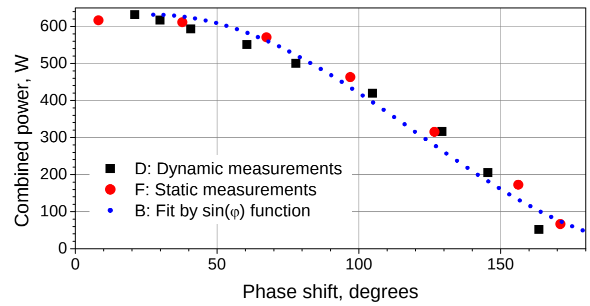

Figure 10: Control of combined power of the injection-locked magnetrons by the phase difference. Dots F and D present power variation at the combiner port "Σ", measured in static and dynamic regimes, respectively. Dots B show fit of the plots D and F by sin(φ) function.

Agreement in the combined powers measured by a calibrated detector and spectrum analyzer, plots D and F, respectively, with the fit trace, plot B, verifies that the method of power control does not disturb injection-locking of the magnetrons and indicates an acceptable linearity and low phase error in the response of the injection-locked 1 kW magnetrons utilizing phase control.

Performance of the injection-locked magnetrons with power combining using fast power control (in dynamic regime) is shown in time domain in Figure 11.

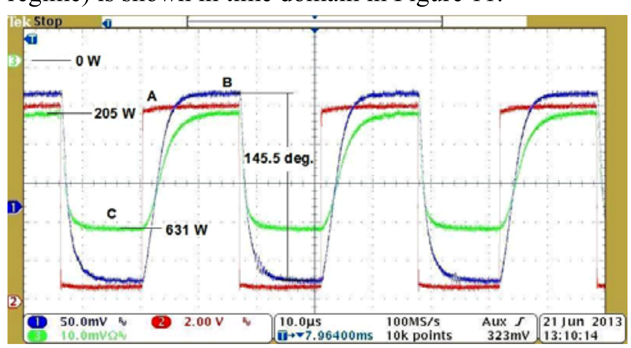

Figure 11: Trace A is shape of the voltage, controlling the phase shifter JSPHS-2484, trace B is the magnetron II phase response on the shifter fast control, trace C shows variation of the power measured by the calibrated detector at the port "Σ" of the 3 dB hybrid.

The measurements were performed at a modulator pulse duration of ≈15 ms. The phase shifter φ_{II} was tuned to get maximum power at the port "Σ" when the control of the JSPHS-2484 phase shifter was OFF. The phase detector trombone φ_I was tuned to avoid saturation in measurements of the phase variations.

Note the bandwidth of control of the analogue phase shifter is ≈50 kHz. Plots B and C show that the bandwidth of the power control of the combined magnetrons is limited by this value, but not by the bandwidth of the magnetron phase control, which is significantly wider, as shown below.

Phase variation of the injection-locked magnetrons with the power combining at modulator pulse duration of 5 ms is shown in Figure 12. Measured high-frequency noise magnitude at t ≥50 μs is ≤ 0.5 degrees (rms) at a combined output power of ≈ 600 W.

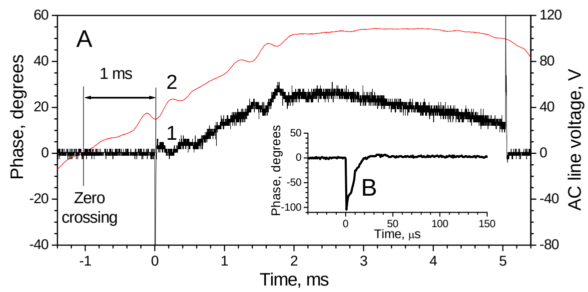

Figure 12: A- phase variations of the combined in power injection-locked magnetrons; B- zoomed in time trace 1.

The bandwidth of the phase control of the injection-locked magnetrons was evaluated using phase modulation in setups shown in figures 3, 6, 9. The injection-locked magnetrons response was compared with the phase-modulated signal of the N5181A generator (at magnitude of the phase modulation of 20 degrees) using the phase detector at various modulating frequencies. Relative distortions of the magnetron phase response associated with measured the phase difference between signals of the generator and the magnetrons output are shown in Figure 13.

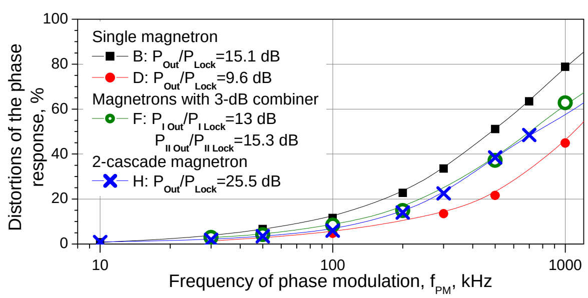

Figure 13: Performance of the injection-locked magnetrons vs. frequency of the phase modulation, f_{PM}, as controlled by the phase-modulated signal.

The plots indicate a wide bandwidth of the phase control (more than 100 kHz), where distortions of the magnetron response are about 10% or less. It implies that the injection-locked magnetron RF source managed in phase and power by a Low Level RF controller with a closed feedback loop at the bandwidth of ≈100 kHz will be able to suppress all expected low-frequency perturbations in SRF cavities, such as parasitic low frequency phase modulation (caused by mechanical oscillations, phase perturbations from beam loading and dynamic tuning errors), perturbations in the magnetrons resulted from power supplies ripples, and induced alternative magnetic fields.

For example, the parasitic modulation caused by HV power supply ripple at frequency f_r=120 Hz will be suppressed within a phase locking loop with an integral gain $I=1.2\cdot10^7$ rad./s, by ≈ $20\cdot\log(I/2\pi\cdot f_r)$ ≈84 dB; phase perturbations at the frequency of 10 kHz will be suppressed by ≈45.6 dB.

Analysis of the discussed above experiments with injection-locked magnetrons demonstrates capability of fast phase control of injection-locked magnetrons and substantiates their operation with a wideband phase control loop. The proposed concept of the CW injection-locked magnetron RF source with a fast vector control looks as feasible for ADS and the intensity-frontier linacs.

Note that experiments described in [4, 11, 12] first verified operation of the injection-locked 1 kW magnetron within a closed control loop.

CONCLUSION

The experiments with 1 kW, CW injection-locked magnetrons operating in pulsed mode with long pulse duration demonstrate the potential of an RF source based on high-power injection-locked magnetrons managed by an appropriate Low Level RF controller. Using a closed feedback loop with a wide bandwidth it will be possible to eliminate all expected low-frequency perturbations in the SRF cavities including perturbations of the magnetron phase stability caused by power supply ripples and induced AC magnetic fields. Performance of the injection-locked magnetrons with a fast power control and quite small rms magnitudes of high-frequency noise (<1 degree), demonstrated in the experiments, indicate that the proposed concept of the RF source based on injection-locked magnetrons will satisfy to the requirements of the intensity-frontier pulsed and CW superconducting linacs applicable for the ADS projects.

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