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A NOVEL TECHNIQUE FOR PULSED OPERATION OF MAGNETRONS WITHOUT MODULATION OF CATHODE VOLTAGE*

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Abstract

Modern pulsed superconducting accelerators of megawatt beams require efficient RF sources controllable in phase and power. It is desirable to have an individual RF power source with power up to hundreds of kW in the millisecond range for each Superconducting RF (SRF) cavity. The efficiency of the traditional RF sources (klystrons, IOTs, solid-state amplifiers) in comparison to magnetrons is lower and the cost of a unit of RF power is higher. The magnetron-based RF sources would significantly reduce the capital and operation costs in comparison with the traditional RF sources. A recently developed kinetic model describing the principle of magnetron operation and subsequent experiments resulted in an innovative technique producing the pulsed "stimulated" generation of magnetrons powered below the self-excitation threshold voltage. This technique does not require pulse modulators to form RF pulses. The magnetron operation in this regime is stable, controllable in phase and power, and provides higher efficiency than other types of RF power sources. It allows operation in pulsed modes with large duty factor. The developed technique and its experimental verification are discussed here.

INTRODUCTION

Magnetrons are presently used in normal conducting compact accelerators as efficient and inexpensive RF self-exciting generators. For superconducting accelerators, the magnetron generators must provide phase and power control with the rates necessary to stabilize the accelerating voltage in SRF cavities [1]. The use of a phase-modulated injected signal to control the phase of the magnetron was first described in [2]. Methods for control of the magnetron phase and power, with the required rates, by injecting resonant (injection-locking) RF signals have been developed recently [3-5]. These methods would provide stabilization of accelerating voltage in a cavity in both phase and amplitude. The phase control is provided via controlling the resonant injected phase-modulated RF signal. The amplitude control is performed via the phase control using vector methods [3, 4] or via the magnetron current control [5]. The last method provides higher transmitter efficiency over a range of power control of ≈10 dB with a bandwidth (presently feasible) about of 10 kHz.

For evaluation of properties of the RF-driven magnetrons and substantiation of the innovative technique, an analytical kinetic model [6] has been developed. The model considers the basic principle of magnetron generation - the resonant interaction of the flow of the phase-grouped Larmor electrons with a synchronous wave. This interaction results in an energy exchange between the wave and the electrons. The developed model enables evaluation of the necessary and sufficient conditions for the coherent generation of the magnetron and predicts and substantiates pulsed coherent generation of the tube driven by a pulsed injected resonant signal and powered without a pulsed modulation of the cathode voltage if it is below the self-excitation threshold.

As follows from the kinetic model, RF generation below the self-excitation threshold enables the maximizing of the efficiency of the magnetrons in a wide range of power control, a reduction of the magnetron noise by the injected signal and looks to be a promising way to extend the magnetron lifetime. A brief description of the advantages of "stimulated" pulsed coherent generation of magnetrons for modern superconducting accelerators with megawatt beams is discussed.

SETUP TO TEST THE STIMULATED GENERATION OF MAGNETRONS

The proof of the principle of this technique was demonstrated with a CW, 2.45 GHz microwave oven magnetron type 2M219G with nominal output power of 945 W and a measured magnetron self-excitation threshold voltage of 3.69 kV. The magnetron was powered by a pulsed High Voltage (HV) source using a partial discharge of the storage capacitor [7], providing a pulse duration of ≈5 ms. The HV source provided negligibly small ripple thus avoiding magnetron start-up caused by the ripple. The pulsed HV source was powered by a charging Glassman 10 kV, 100 mA switching power supply with voltage control.

Pulsed "stimulated" generation of the magnetron was realized by the injection of a pulsed locking signal into the magnetron RF system. This has been studied with the setup shown in Fig. 1. The CW signal of an HP-8341A generator was converted to RF pulses by a mixer (ZEM-4300MH from Mini-Circuits) controlled by a pulsed generator (type 100A). Then the RF pulses were amplified by solid-state and TWT amplifiers which provided a pulsed RF signal with power up to 160 W to drive the magnetron. Pulse shapes and power levels of the injected signal and the magnetron output signal were measured by the RF detectors with Schottky zero-bias diodes calibrated to better than ±0.5%. The magnetron pulse current was measured by a current transducer (type LA 55-P) with a circuit integration time of about 50 μs.

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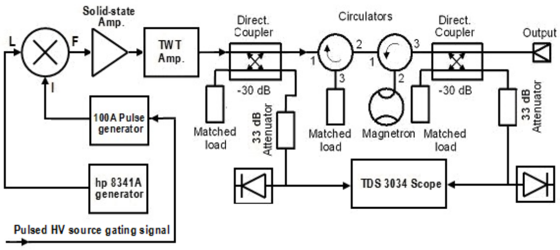

Figure 1: Setup to study the ON-OFF switch control of the magnetron driven by a pulsed resonant injected signal.

PROPERTIES OF THE MAGNETRON GENERATING BELOW THE SELF-EXCITATION THRESHOLD VOLTAGE

The magnetron powered below the threshold of self-excitation may operate in the mode of "stimulated" generation. Such an operation requires a limitation of the cathode voltage to stop the generation when the injected resonant signal is switched OFF. Measured maxima and minima of the magnetron cathode voltage and current allowing the "stimulated" pulsed generation of the magnetron 2M219G at various power levels of the injected signal, PLock are plotted in Fig. 2. The solid lines in the plot show the ranges of the magnetron cathode voltage (and the magnetron current) allowing stable operation in the "stimulated" generation mode. The injected signal duration for the measurements was 2.2 ms with a magnetron cathode voltage duration of 5.1 ms.

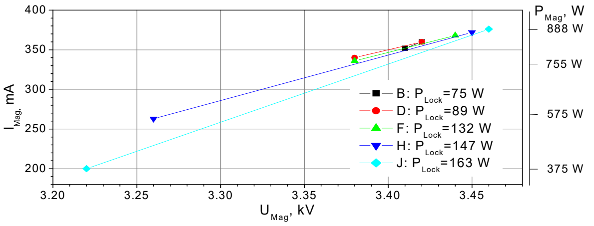

Figure 2: The ranges of the 2M219G tube cathode voltage and the magnetron current in the "stimulated" generation mode at various power levels of the injected resonant signal PLock. The right scale shows the measured RF power of the magnetron vs. the magnetron current, IMag.

The measurements show that with "stimulated" generation the magnetron can provide almost nominal output power at a lower cathode voltage. The efficiency of generation in "stimulated" mode is notably higher than the efficiency at operation above the self-excitation threshold with low power (≤-20 dB) of the injected resonant signal [8]. This is due to the improved phase grouping and reduced losses of drifting charges with sufficient amplitude of the synchronous wave [5].

Figure 2 indicates the possibility of power control of the magnetron by regulation of the cathode voltage in an admissible interval depending on P_{Lock}. The relative variation of the magnetron output power, $\Delta P_{RF}/P_{RF}$, requires smaller variation of the magnetron cathode voltage $\Delta U_{Mag}/U_{Mag}$:

$$\Delta P_{RF}/P_{RF} \approx (Z_S/Z_D)\cdot\Delta U_{Mag}/U_{Mag}.$$

Here Z_S and Z_D are the static and dynamic magnetron impedances, respectively; typically $Z_S \geq 10\ Z_D$.

The measurements indicate that an increase of the injected signal increases the difference between the maximum and minimum power of the RF pulse generated by the magnetron. The maximum and minimum powers are determined mainly by the maximum and minimum cathode voltage.

Figure 3 showing the maximum and minimum powers of the magnetron operating in the "stimulated" generation mode vs. the P_{Lock} value demonstrates that the injected RF signal of -8 dB allows a regulation of the magnetron power in the range of ≈ 3 dB. For magnetron power regulation in the range of 7 dB the injected signal with P_{Lock}≈170 W (-7.4 dB) is required.

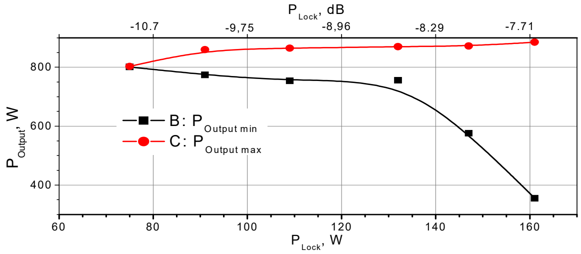

Figure. 3: Measured maximum and minimum output power levels of the 2M219G magnetron operating in the "stimulated" mode vs. PLock.

Figure 4 shows 4 kHz trains of 147 µs RF pulses for the injected and the magnetron output signals, as well as the magnetron current and the HV pulse of 5.1 ms duration. One can see the magnetron switching ON-OFF due to the injected resonant signal without pulsed modulation of the cathode voltage.

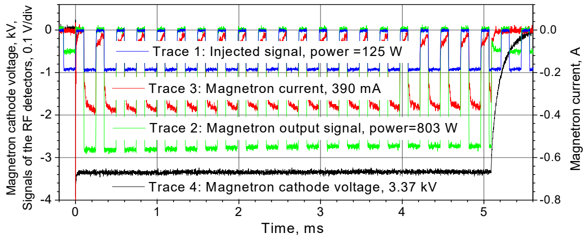

Figure 4: 4 kHz trains of 147 µs pulses (duty factor of ≈59%). Traces 1 and 2 - the resonant injected and the magnetron output RF signals with powers of 125 W and 803 W, respectively; trace 3 - the magnetron pulsed current; trace 4 - the magnetron cathode voltage.

The plots show a decrease of the magnetron current (by 4.4±0.5%) during the 5.1 ms HV pulse. The decrease is caused by the discharge (~0.4%) of the HV source storage capacitor. This results in the measured decrease of the magnetron output power (≈ 4.9%). A part of the power of the injected signal (<40% of the locking power P_{Lock}) goes to the magnetron output. It is clearly seen when the magnetron cathode voltage is OFF.

Measured with better time resolution the traces of a 20 kHz train of 13 µs long RF signals injected into the magnetron and the output signals, are shown in Fig. 5.

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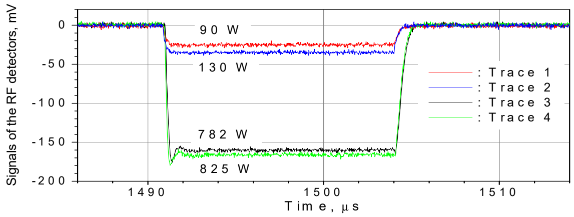

Figure 5: 13 µs pulses of the measured 20 kHz trains when the magnetron operates in the "stimulated" generation mode. Traces 3 and 4 are the magnetron output RF signals which depend on the power of driving signals shown in traces 1 and 2, respectively.

All traces in Fig. 5 demonstrate quite short rise and fall times when the magnetron is switched ON or OFF by the injected resonant signal. These times do not exceed 200 ns that roughly corresponds to ~ 200 cyclotron periods.

The magnetron efficiency η, is the ratio of generated RF power to consumed power: $\eta \approx P_{RF}/(U_{Mag} \cdot I_{Mag}+P_{Lock})$. Here: U_{Mag} and I_{Mag} are the measured values of the magnetron voltage and current, P_{Lock} is the power of the injected resonant signal. The measured efficiency of the 2M219G magnetron vs. P_{Lock} value in for minimum and maximum output power, admissible for the "stimulated" generation mode is shown in Fig. 6.

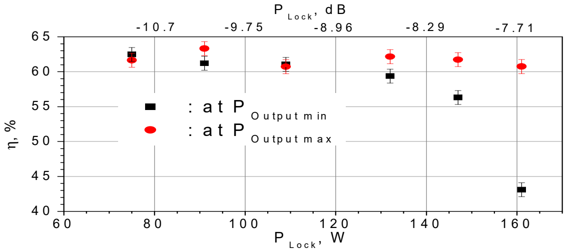

Figure 6: Dependence of conversion efficiency of the 2M219G magnetron on power of injected signal P_{Lock}.

The measured conversion efficiency of the magnetron operating above the self-excitation threshold ("free run") mode ($U_{Mag} \approx 3.69$ kV, $P_{Lock} = 0$), is ≈ 54%.

The magnetron with cathode voltage above the ranges shown in Fig. 2, but still below self-excitation threshold, continues generation even after the injected signal is switched OFF, Fig. 7.

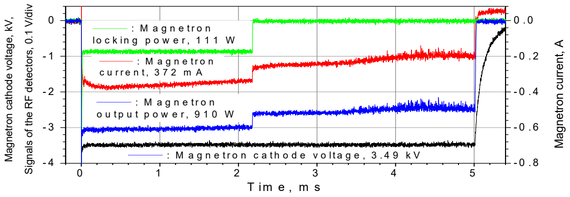

Figure 7: Continuation of the magnetron generation at a magnetron voltage higher than is required for the "stimulated" generation at the given P_{Lock} after the injected signal is switched OFF.

The generation continuation without the injected signal in this case can be explained by the finite damping time of the synchronous wave.

Shown in Fig. 7 the noise in the traces of the magnetron current and the RF output power appears because of loss of coherency in this situation where the locking signal is switched OFF, but the generation still continues at a cathode voltage less than the self-excitation threshold [6]. The noise is absent when the magnetron cathode voltage is in the range admissible for the "stimulated" generation mode [8].

Using a two-stage magnetron RF source [3, 6], composed of small and high-power magnetrons (both tubes operating in the "stimulated" generation mode) it is possible to reduce the power of the resonant signal controlling the RF source by ≈10 dB. This will reduce the capital cost of the driver module. In this case a powerful magnetron can provide highly efficient power control in the middle frequency band and broadband phase control by a resonant driving signal with a power level of about -17 dB from the nominal power of the output magnetron.

SUMMARY

We have developed an innovative technique allowing pulsed RF generation of a magnetron without modulation of the cathode voltage, while the tube is powered below the self-excitation threshold. This increases reliability of the magnetron operation. A pulsed resonant injected signal with power ≥ -11 dB of the magnetron nominal power is required for such operation. The technique was substantiated by the developed kinetic model of magnetron operation representing the principle of RF coherent generation of the tube. Experiments with a 2.45 GHz magnetron proved the developed technique. Magnetrons powered below the self-excitation threshold and driven by a resonant signal ≥-10 dB provide higher conversion efficiency, significantly lower (by ≈20 dB/Hz) spectral power density of noise and significantly wider (up to hundreds of kHz) the phase control bandwidth.

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