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NOVEL MAGNETRON OPERATION AND CONTROL METHODS FOR SUPERCONDUCTING RF ACCELERATORS*

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Abstract

High power magnetrons designed and optimized for industrial heating, were suggested to power (in injection-locked mode) superconducting RF cavities for accelerators due to lower cost and higher efficiency. However, standard operation methods do not provide high efficiency with wideband control suppressing microphonics. We have developed and experimentally verified novel methods of operating and controlling the magnetron that provide stable RF generation with higher efficiency and lower noise than other RF sources. By our method the magnetrons operate with the anode voltage notably lower than the self-excitation threshold improving its performance. A magnetron operating with the anode voltage below the self-excitation threshold, in so-called stimulated coherent generation mode has special advantage for pulse regime without a modulation of the cathode voltage. This eliminates the need for expensive pulsed HV modulators and additionally increases the magnetron RF source efficiency due to absence of losses in HV modulators.

INTRODUCTION

Modern superconducting RF (SRF) accelerators require efficient RF sources controlled dynamically in phase and power to eliminate parasitic modulations caused by microphonics, etc. The stability of accelerating field in SRF cavities is supported by a wideband phase and power control of RF sources.

The efficiency of the traditional RF sources (klystrons, IOTs, solid-state amplifiers) compared to magnetrons is lower and the capital cost of RF power per Watt is much higher [1-3]. Therefore, the magnetron-based RF sources could significantly reduce the capital and operation costs of superconducting modern accelerators.

Phase control of a magnetron by a phase-modulated injection-locking signal was proposed and verified for a 2.45 GHz SRF cavity operating at 2 K [4]. The methods for control of the magnetron phase and power in a wide band have been developed and described in [5-7].

All mentioned methods use a phase-modulated injection-locking signal for the phase control. The wide-band vector power control is realized with vector summing by a 3 dB hybrid of output signals of a two-channel magnetron RF source controlled in phase [5], or in a single-channel RF source controlling the spectral power on the fundamental frequency by modulation of the depth of phase modulation [6]. If the modulation frequency is much larger than the SRF cavity bandwidth, the sidebands caused by the modulation are reflected from the SRF cavity into a dummy load. Both vector methods of power control use fast redistribution of the RF power between the cavity and a dummy load; that considerably reduces the average efficiency with vector methods of control.

The method of power control described in [7] uses a magnetron current control in a magnetron driven by a large injected signal (≈ -10 dB of the tube nominal power). In such operation the spectral density of noise power is lower by ≈ 20 dB/Hz than for a magnetron injection-locked by a small signal (≤ -20 dB) [7, 8]. In accordance with the kinetic model of a resonant interaction of electrons with the synchronous wave in a magnetron [8], the increased injection-locking signal provides better phase grouping of electrons delivering onto the anode. In this case the tube stably operates with the anode voltage below the self-excitation threshold and the magnetron power is controlled in the range of ≈ 10 dB. This method provides power control with the average efficiency higher compared to the mentioned above vector methods. The control bandwidth depends on the bandwidth of power supply providing the magnetron current regulation. Combining this method with one of vector methods enables a wideband phase and power control of magnetrons with higher efficiency and lower noise.

Recent study of operation of magnetrons in "subcritical" mode (below the self-excitation threshold voltage) enabled unknown earlier the stimulated coherent generation mode with improved phase grouping, applicable for CW or pulse RF generation [9]. In this mode a magnetron provides advanced features most suitable for SRF accelerators. Experimental verification of the novel methods of operation and control are presented below.

IMPACT OF THE INJECTION-LOCKING SIGNAL ON A MAGNETRON WORK

Traditionally is implied that the magnetrons feeding the SRF cavities operate above the self-excitation threshold voltage, being driven by a quite small injection-locking signal (≤ -20 dB of the tube nominal power). Studying the impact of injected signal on a magnetron operation we found non-standard regimes that provide better stability, higher efficiency, lower noise and much better controllability of magnetrons at a quite large injection-locking signal due to better phase grouping of electrons in "spokes". In this regime the magnetron operates as a coherent, precisely stable, low-noise forced oscillator with the carrier frequency line width, $\Delta f / f < 10^{-9}$ [7], providing a wideband efficient phase and power control necessary to stabilize accelerating field in SRF cavity.

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Verification of these features is presented in the following figures.

Figure 1 shows the carrier frequency offset of the 2.45 GHz, 1.2 kW injection-locked magnetron type 2M137-IL in CW mode [7], measured with spectrum analyzer type E4445A at the resolution bandwidth of 5 Hz vs. power of injection-locking signal, P_{Lock}.

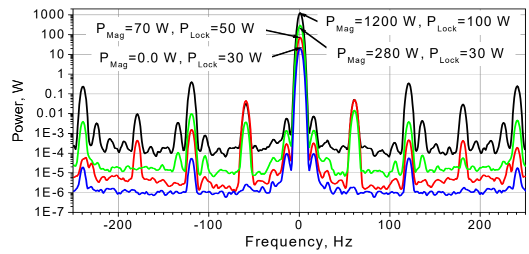

Figure 1: Offset of the carrier frequency of magnetron type 2M137-IL at various powers of magnetron output, P_{Mag}, and the injection-locking signal, P_{Lock}. The trace P_{Mag} = 0.0 W, P_{Lock} = 30 W shows the frequency offset of the locking signal when the magnetron anode voltage is OFF. The trace P_{Mag} = 70 W, P_{Lock} = 50 W shows operation in so-called stimulated coherent generation mode.

As it is shown in [8], the large injection-locking signal at the magnetron anode voltage below the self-excitation threshold reduces fluctuation of the synchronous wave, increases efficiency and reduces spectral density of noise.

We studied impact of strength of the injection-locking signal on the bandwidth of the magnetron control measuring transfer function magnitude characteristic in phase modulation domain [5] and measuring transfer function phase characteristic [8], with 2.45 MHz, 1 kW magnetrons operating in pulsed mode at the pulse duration of 5 ms, using the injection-locking phase-modulated signal.

The admissible bandwidth of the phase and power dynamic control of magnetrons is determined by stability of the LLRF system with feedback loops. The bandwidth of control was determined by measured transfer function characteristics for levels of the magnitude and phase characteristics of -3 dB and 45 deg., respectively, assuming first order filters in the LLRF system. Figure 2 shows the admissible bandwidth of control, BW_C, of 2.45 GHz microwave oven magnetrons vs. the locking signal power.

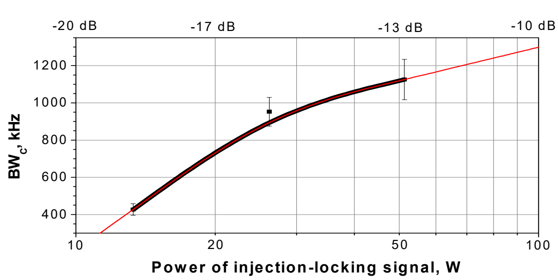

Figure 2: The admissible bandwidth of control of 2.45 GHz microwave oven magnetrons determined by measured transfer function characteristics. Black bold line shows the range and results of measurements, red lines show extrapolation with B-spline fit.

Plots in Fig. 2 show that the locking signals ≥ -15 dB increase the control bandwidth approximately logarithmically. For first order filters the out-of-band roll-off is 20 dB/decade. For L-band magnetrons intended for modern SRF accelerators one can expect the bandwidth of control of about 100-500 kHz. This will allow attenuation of parasitic microphonics modulation by more than 60 dB.

STIMULATED COHERENT GENERATION MODE FOR MAGNETRONS

This mode of magnetrons operation, uses quite large injection-locking signal at the magnetron anode voltage below the self-excitation threshold. The mode is realized in CW and pulse regimes allowing 100% pulse modulation of the synchronous wave by a gated injection-locking signal. This makes possible a pulse operation of a magnetron without modulation of cathode voltage [9]. Figure 3 shows setup to study the stimulated coherent generation mode with a 2.45 GHz, 945 W magnetron.

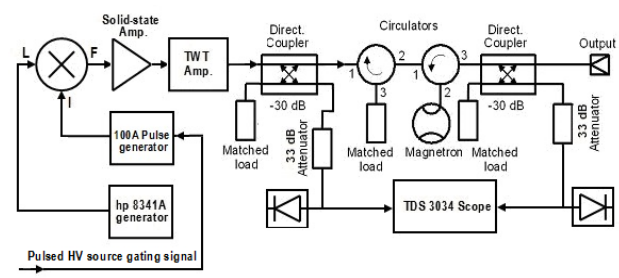

Figure 3: Setup to study the pulse control of the magnetron type 2M219G driven by a gated locking signal.

The magnetron was fed by a pulsed (5 ms) power supply with very low ripple. The measured anode voltage, current and power ranges of the tube are shown in Fig. 4.

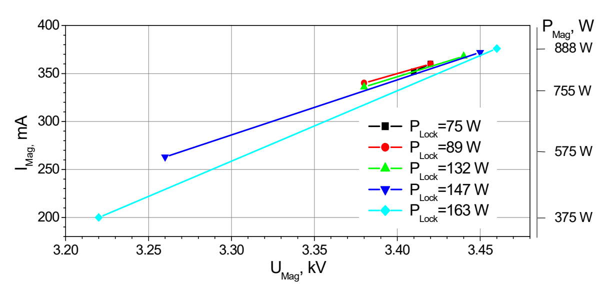

Figure 4: The ranges of the 2M219G magnetron anode voltage and the magnetron current in the stimulated generation mode vs. power of the injection-locking signal P_{Lock}. The right scale shows measured RF power of the magnetron in accordance with the magnetron current.

Measured self-excitation threshold voltage for used 2M219G magnetron is 3.69 kV. In the stimulated coherent generation mode, the magnetron stably operates at the anode voltage ≤3.46 kV in both CW and pulse regimes. Thus, operation in this mode is a promising way to increase the magnetron reliability and longevity.

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Plots in Fig. 4 shows that the efficient method of power control by regulation of the magnetron current [7] is applicable to the developed mode.

Pulse operation of magnetrons in stimulated coherent generation mode with 100% pulse modulation of the synchronous wave, without modulation of the cathode voltage is shown in Fig. 5 [9].

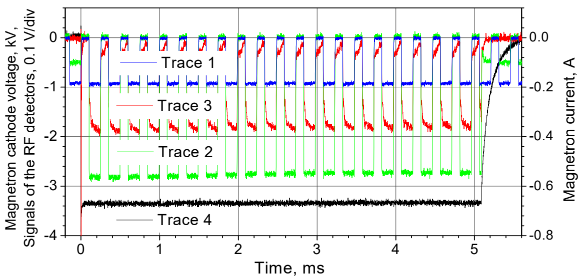

Figure 5: 4 kHz trains of 147 µs pulses (duty factor of ≈ 59%). Traces 1 and 2 - the injection-locking and the magnetron output RF signals with powers of 125 W and 803 W respectively; trace 3 - the magnetron pulsed current (right scale); trace 4 - the magnetron cathode voltage (-3.37 kV).

Advantages of the stimulated coherent generation mode comparing to traditional regime tested with type 2M219G magnetron are listed in Table 1 [9].

Table 1: Comparison of Traditionally Used Regime of Operation and Control for 2M219G Magnetron with Operation in Stimulated Coherent Generation Mode

Parameters	**Traditionally used regime**	**Regime of stimulated RF generation**
Locking power, P_{Lock}	≤ -20 dB	-11 to -7.4 dB
Anode voltage, kV	≥3.69	3.22 to 3.46
Power control range by current variation	≈ 1.8 dB	≈ 7 dB
Conversion efficiency	54%	≈ 62%
Bandwidth of control	<0.2 MHz	≈ 1.5 MHz
Spectral density of noise power, dBc/Hz	~ -90	< -110
Average efficiency in 7 dB range power control	Not applicable	≈ 57.5%

Traces of the gated injection-locking and output signal of the 2M219G magnetron in the stimulated coherent generation mode measured with higher time resolution are shown in Fig. 6 [9].

The rise and fall time of the magnetron switched ON or OFF by the injection-locking signal (Fig. 6) is of about 200 ns at the measuring circuit integration time ~ 100 ns. This corresponds to predictions of the kinetic model of a magnetron operation [8].

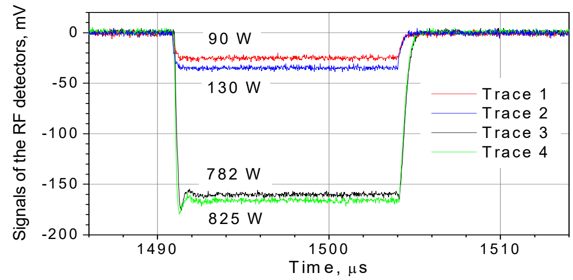

Figure 6: The 13 µs pulses of the measured 20 kHz trains. of the magnetron operating in the stimulated coherent generation mode. Traces 3 and 4 are the magnetron output RF signals in dependence on the power of driving signals shown in traces 1 and 2, respectively.

SUMMARY

We have developed an innovative method of controlled pulsed RF generation of a magnetron without modulating the cathode voltage. This will significantly reduce the cost of pulse RF sources and further increase their efficiency due to the absence of power losses in HV modulators. The method was substantiated by the developed model of a resonant interaction of Larmor electrons in "spokes" with a synchronous wave. The magnetron operating in the mode of stimulated RF generation has efficiency higher than when it operates in a "free run" mode or being driven by a small (≤ -20 dB) injected signal due to better phase grouping. A power control by controlling magnetron current in the stimulated coherent generation mode of operation will provide higher average efficiency in a wide-range control than other known power control methods. A magnetron operating with the injected signal ≥ -11 dB also provides significantly lower (by ≈ 20 dB/Hz) spectral power density of noise and enables the phase and power control in a wide band. Due to lover anode voltage the stimulated operation mode for magnetrons is a promising way to increase their reliability and lifetime.

The developed mode of magnetron operation demonstrates features that make the magnetron based RF power source an attractive option for modern superconducting CW and pulse accelerators.

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