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NOVEL MAGNETRON OPERATION AND CONTROL METHODS FOR SUPERCONDUCTING RF ACCELERATORS

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High power magnetrons designed and optimized for industrial heating, with injection-locking, have been suggested to power superconducting RF cavities for accelerators due to lower cost and higher efficiency [1-3]. But, the standard operation methods do not provide high efficiency at a wideband control to suppress microphonics and other parasitic modulations. We have developed and experimentally verified novel methods of a magnetron operation and control to produce stable RF generation with efficiency higher and noise power lower compared to other RF sources.

New methods of magnetrons operation

Our methods utilize improved phase grouping of electrons in "spokes" at a large injection-locking signal. Therefore, a magnetron may operate with the anode voltage below the self-excitation threshold. This enables wide-band efficient power control in a wide range, increases stability, reduces noise [4, 5], improving a magnetron performance necessary for SRF accelerators.

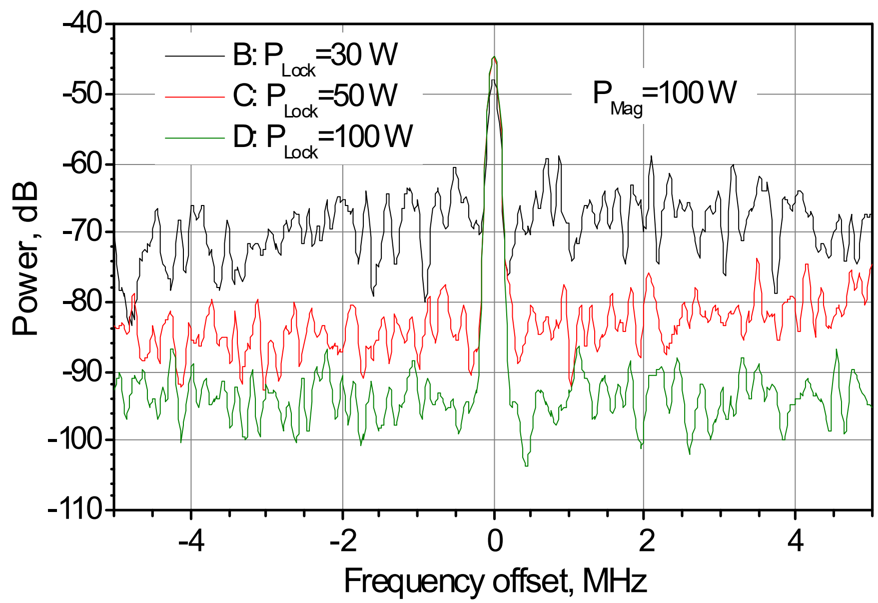


Fig. 1. Impact of the locking signal on the magnetron performance at low output power.

Average efficiency of a magnetron power control with various control methods

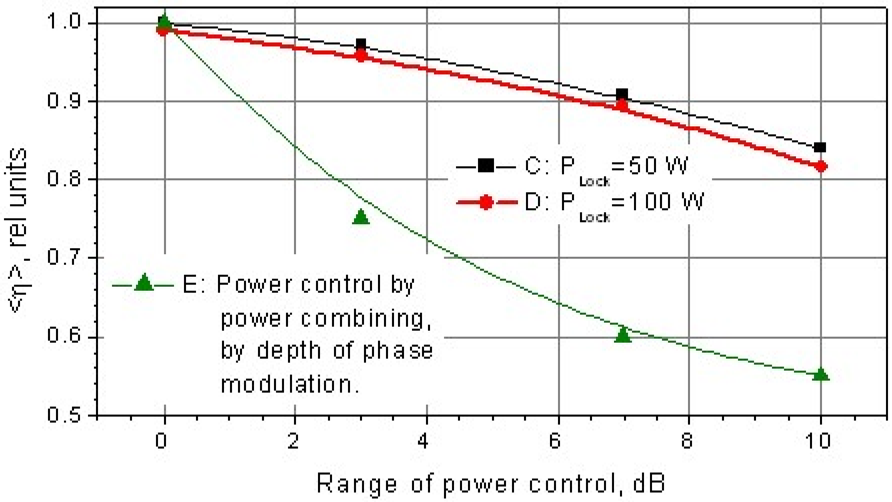
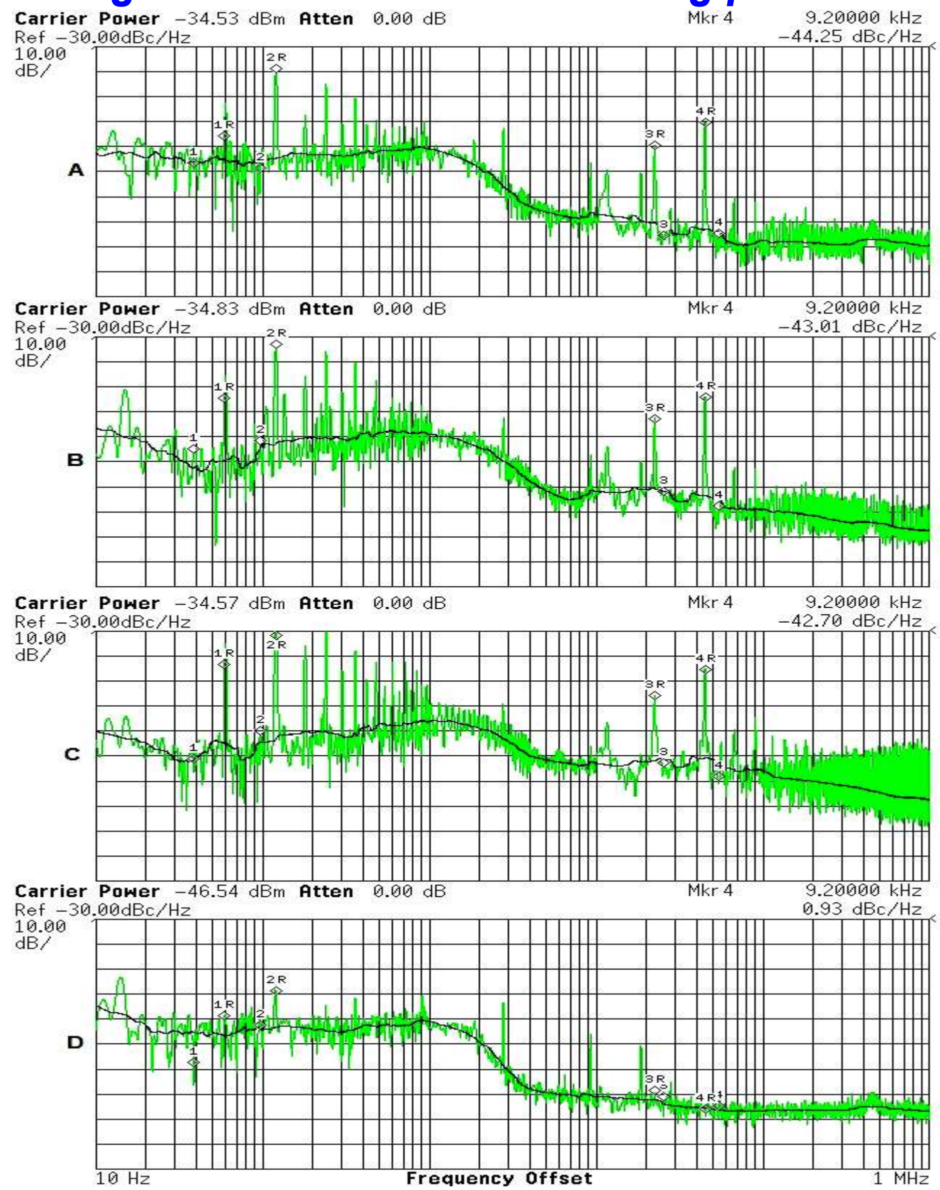


Fig. 2. A magnetron average efficiency of power control with various methods vs. the range of control [5, 6, 7]. C, D- power control varying the current of the tube with a large locking signal, E- using vector methods of power control.

Fig. 3. Traces A, B, C- the locking power of 100, 30, 10 W, respectively. Trace D- spectral power density of noise of the master oscillator [4].

Spectral power density of a 2.45 GHz, 1 kW magnetron noise vs. the locking power



IMPACT OF THE INJECTION-LOCKING SIGNAL ON A BANDWIDTH OF A MAGNETRON CONTROL

Impact of injection-locking signal strength on the magnetron control bandwidth was determined from the transfer function magnitude and phase characteristics of a 2.45 GHz, 1 kW magnetron [4, 5].
The admissible bandwidth of the phase and power control of magnetrons is determined by the stability of LLRF system, implying first order filters in the feedback loops for a dynamic control. There are used levels of the measured transfer function magnitude and phase characteristics of -3 dB and 45 deg., respectively.

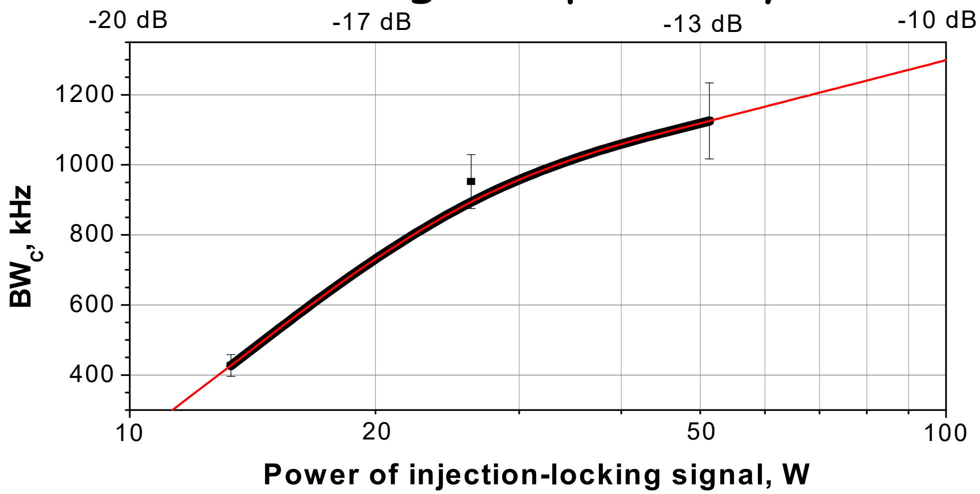


Fig. 4. Admissible bandwidth of control of a 2.45 GHz, 1 kW magnetron vs. the injection-locking signal.

For first order filters the out-of-band roll-off is 20 dB/decade. For L-band magnetrons intended for modern SRF accelerators one expects the bandwidth of control of about 100-500 kHz. This will allow attenuation of parasitic modulation by more than 60 dB.

STIMULATED COHERENT GENERATION MODE FOR MAGNETRONS

This mode of operation, uses quite large injection-locking signal combined with the magnetron anode voltage below the self-excitation voltage. We called it a “stimulated coherent generation mode”. The mode is realized in CW and pulse regimes enabling 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 [8].

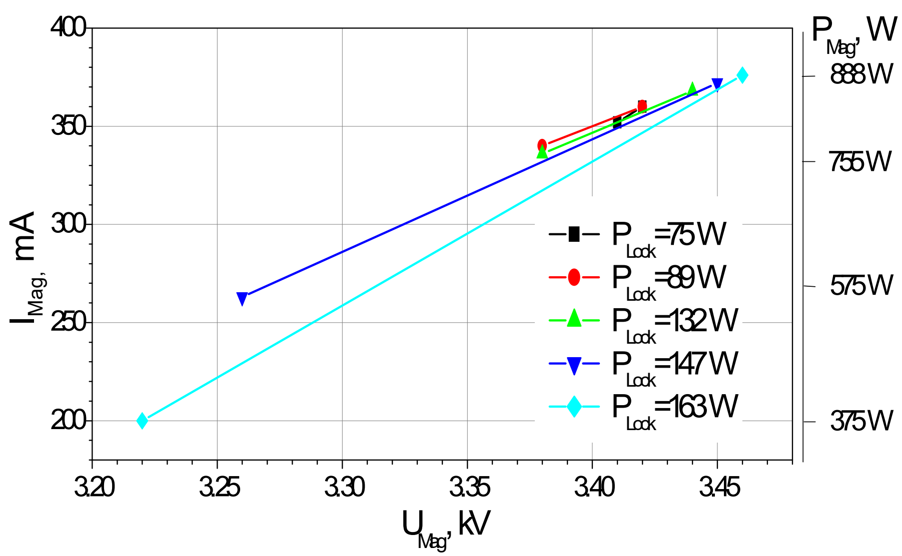


Fig. 5. The magnetron anode voltage, current and RF power ranges vs. the locking signal power.

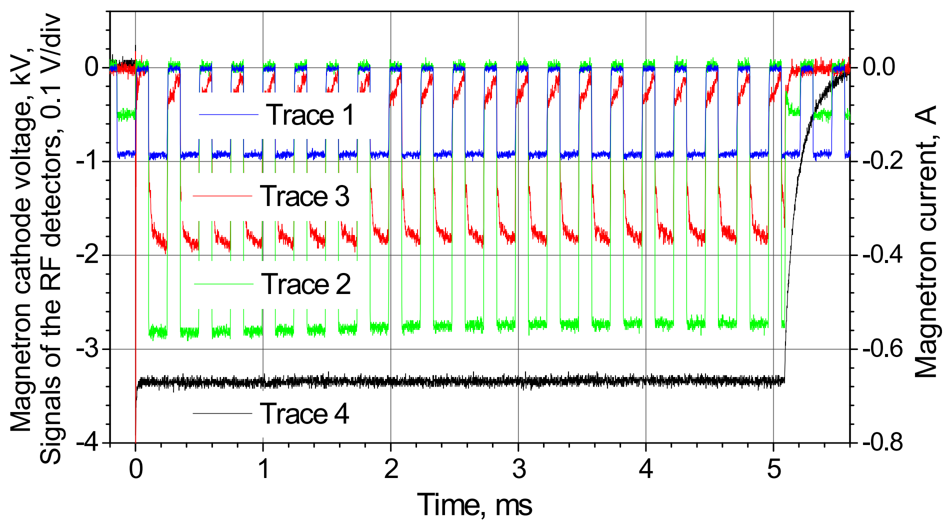


Fig. 6. Traces 1 and 2 - the 125 W locking and the 803 W output magnetron signals, respectively; 3 - the magnetron pulsed current (right scale); 4 - the magnetron cathode voltage (-3.37 kV).

Traces of the gated injection-locking and output signals of the 2M219G magnetron that were measured with higher time resolution are shown in Fig. 7.

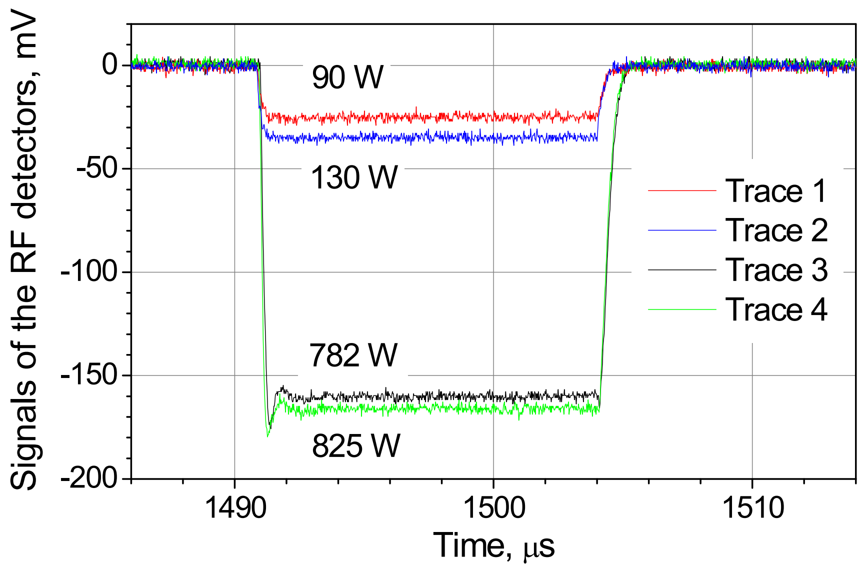


Fig. 7. The 20 kHz measured trains with 2.45 GHz magnetron operating in the stimulated coherent generation mode. Traces 3 and 4 are the magnetron output RF signals in dependence on the power of driving signals shown in traces 1 and 2, respectively [6].

Advantages of the stimulated RF generation mode comparing to traditional regime are listed bellow:

Parameters	Traditionally used control	Control in stimulated RF generation
P_{Lock}	≤ -20 dB	-11 to -7.4 dB
Anode voltage,	≥3.69 kV	3.22 - 3.46 kV
Power control range by current variation	≈1.8 dB	≈7 dB
Conversion efficiency	54%	≈62%
Bandwidth of phase control	<0.2 MHz	≈1.5 MHz
Spectral density of noise power	~ -90 dBc/Hz	< -110 dBc/Hz
Average efficiency in 7 dB range power control	Not applicable	≈57.5%
100% pulse modulation by the locking signal without a HV modulator	Not applicable	Applicable

SUMMARY

We have developed an innovative technique enabling pulsed RF generation of a magnetron without modulation of the cathode voltage. The technique was substantiated by the developed model of the magnetron operation [4]. 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) injection-locking signal. A power control by controlling magnetron current in the stimulated mode of operation provides higher average efficiency in a wide range of control than other power control methods applicable for SRF accelerators [5, 6]. A magnetron operating with the injected signal ≥ -11 dB also provides significantly lower (by ≈ 20 dB/Hz) spectral power density of noise [4] and enables the phase control in a wide band. 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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