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ON FORCED RF GENERATION OF CW MAGNETRONS FOR SUPERCONDUCTING ACCELERATORS*

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Abstract

CW magnetrons, developed for industrial RF heaters, were suggested to power superconducting RF (SRF) cavities of accelerators due to magnetrons higher efficiency and lower cost comparing to traditionally used klystrons, IOTs or solid-state amplifiers. CW magnetrons are regenerative RF generators with a huge regenerative gain. This causes regenerative instability with a quite large noise. Traditionally CW magnetrons operate at the anode voltage above the threshold of self-excitation. Stabilized by a small injection-locking signal they were proposed to drive SRF cavities. Then the magnetrons generate the injection locked oscillations and generate noise. This may preclude use of CW magnetrons in some SRF accelerators. We developed described below a mode for forced RF generation of CW magnetrons when the injected forcing signal provides start up and the regenerative noise is suppressed. The mode is most suitable for powering high Q-factor SRF cavities.

INTRODUCTION

High-power CW magnetrons, designed and optimized for industrial RF heaters, but driven by an injection-locking signal, were suggested in number of works to power SRF cavities in accelerators due to higher efficiency and significantly lower cost of generated RF power per Watt than traditionally used RF amplifiers (klystrons, IOTs, solid-state amplifiers). The RF amplifiers driven by a master oscillator serve as coherent low noise RF sources. The CW magnetrons are regenerative RF generators with a huge regenerative gain of the resonant system to start up reliably with a self-excitation by noise even if the tube is powered by a DC power supply. Very large regenerative gain causes a regenerative instability with a large level regenerative noise. Traditionally the magnetrons operate in the self-excitation mode, i.e. with the anode voltage above the self-excitation threshold, at a small injection-locking signal, $P_{Lock} \approx$ -20 dB$_C$ or less of the magnetron power P_{Mag}. In this case the regenerative noise of a CW magnetron violates a necessary correlation of the tube start up with its injection-locking; the magnetron may be launched by the noise or Power Supply (PS) ripples via side bands, but not by the injection-locking signal. Such probability is considered in the presented work. A novel method of forced RF generation of CW magnetrons eliminating start up by noise and PS ripples is briefly described below. The method was tested in experiments with CW magnetrons of microwave ovens.

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OPERATION OF A CW MAGNETRON INJECTION-LOCKED BY A SMALL SIGNAL

We consider operation of a CW magnetron as it is traditionally assumed, in the self-excitation mode, at an injection-locking signal with low power P_{Lock}.

The effective bandwidth of injection-locking Δf, at the locking signal is expressed by the following equation [1]:

$$\Delta f = \frac{f_0}{2Q_L}\sqrt{\frac{P_{Lock}}{P_{Mag}}} \quad (1)$$

Here: f_0 is the instantaneous magnetron frequency, Q_L is the magnetron loaded Q-factor, P_{Mag} is the magnetron output power. For the 2.45 GHz, free running microwave oven magnetron type 2M137-IL the effective bandwidth Δf_{FR} ≈4.5 MHz [2]. Out of the effective bandwidth the magnetron cannot be injection-locked at the given P_{Lock}.

Then the probabilities of the injection-locking process w_{Lock} and a free running operation w_{FR} (P_{Lock} =0) for this 2.45 GHz, CW tube one can estimate as:

$$w_{Lock} \sim \frac{\Delta f}{\Delta f_{FR}}, \text{ and } \quad w_{FR} \sim \frac{\Delta f_{FR} - \Delta f}{\Delta f_{FR}} \quad (2)$$

The probabilities estimates vs. P_{Lock} are shown in Table 1.

Table 1: The Values of w_{Lock} and w_{FR} vs. P_{Lock}.

P_{Lock}	Δf,	w_{Lock}	w_{FR}
-10 dB	3.87 MHz	~0.86	~0.14
-20 dB	1.22 MHz	~0.27	~0.73
-30 dB	0.39 MHz	~0.09	~0.91

Thus, probability of the injection-locked generation of such RF source may be less than probability of the free running generation caused by noise. The noise oscillations are much less in magnitude than the injection-locked ones. Since the average time of motion of charges in the interaction space towards the anode is $\sim f_0^{-1} << Q_L/\pi f_0$ (the latter is a filling time of the magnetron resonant system), this results in a notable quasi-continuous noise spectrum. It is a disadvantage for operation of the self-exciting magnetrons with low locking signal for high Q-factor SRF cavities. The distorted spectra of the RF sources with an intense quasi-continuous noise may preclude required suppression of parasitic modulations (microphonics, etc.) and may increase the beam emittance in SRF accelerators.

Impact of power of the injection-locking signal on the spectral density of noise power for the 2.45 GHz microwave oven free running magnetron plotted in Fig. 1 [3]

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shows a significant (by ~20 dBc/Hz) increase of the spectral density of noise power at 100 kHz ≤ $|f_{Lock} - f_0|$ ≤1 MHz. This indicates low probability of the injection-locking process at the locking signal $P_{Lock} = 10$ *W* (-20 dBc)..

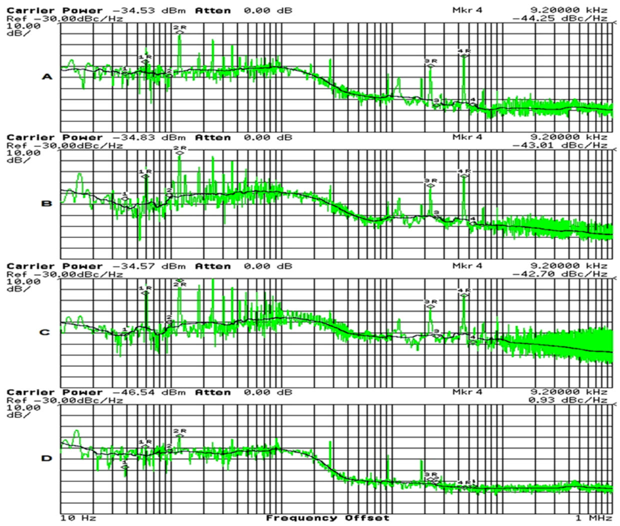

Figure 1: The spectral density of noise power relatively f_c of the magnetron 2M137-IL at the output power of 1 kW, at the locking signal of 100, 30, and 10 W, traces A, B, and C, respectively. Traces D are the spectral density of noise power of the injection-locking signal (P_{Lock} =100 W), when the magnetron feeding voltage is OFF.

OPERATION OF CW MAGNETRONS ABOVE AND BELOW THE SELF-EXCITATION THRESHOLD VOLTAGE

Measured with bandwidth resolution of 5 Hz, Fig. 2, the carrier frequency offset shows quasi-continuous noise, significantly reduced when the tube operates below the self-excitation threshold voltage [3].

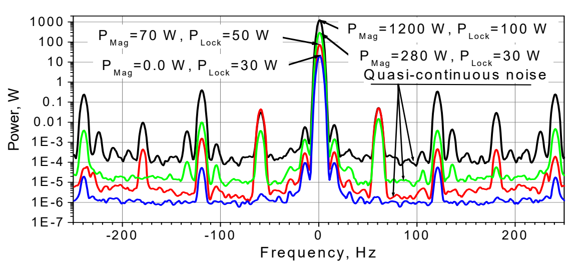

Figure 2: Offset of the carrier frequency of the magnetron type 2M137-IL (operating in CW mode) with the threshold of self-excitation of 4.04 kV at various power levels of magnetron output, P_{Mag}, and the injection-locking (forcing) signal, P_{Lock}.

The trace P_{Mag} =0.0 W, P_{Lock} =30 W shows the frequency offset of the injection-locking signal when the magnetron anode voltage is OFF. The traces P_{Mag} =70 W, P_{Lock} =50 W and P_{Mag} =280 W, P_{Lock} =30 W show the tube operation below the self-excitation threshold voltage. The trace P_{Mag} =1200 W, P_{Lock} =100 W relates to operation above the self-excitation voltage. The tube anode voltages U_{Mag} in this experiment were 3.90, 4.01 and 4.09 kV, respectively.

Traces in Fig. 2 show that the ratios of carrier frequency peaks to quasi-continuous noise are largest at operation below the self-excitation voltage. A noticeable value of quasi-continuous noise at the traditionally used operation of magnetrons above the self-excitation voltage indicates a high probability of incoherent generation, i.e., reduced probability of the injection-locking process.

Using the model of the charge drift approximation [4] and equations in polar coordinates for motion of electrons in a magnetron [5], we found the necessary and sufficient conditions for launching and operation of magnetrons for the tubes fed even below the Hartree voltage [3]. Considering RF generation of magnetrons as non-stationary processes, makes it possible to find the mode of operation and control of magnetrons as coherent RF sources with maximum efficiency, phase and power controllability in a wide frequency band, with a much lower the spectral density noise power [6].

Figure 3 shows total noise power $P_{RN} + P_{SN}$, excluding sidebands vs. the tube anode voltage at various injected resonant signals and the output carrier peak power P_{Mag} as it is plotted in Fig. 2 [6]. It is seen that reducing the magnetron anode voltage allows greatly reduce the tube noise.

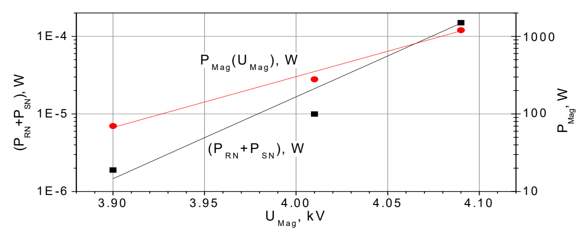

Figure 3: Dependences of the magnetron total noise power (black dots, left scale) and the output power (red dots, right scale) vs. the anode voltage. Solid lines show the exponential fits of build-ups of the output power, P_{Mag} and $P_{RN}+P_{SN}$ power for the magnetron 2M137-IL [6].

Affect of the phase grouping on the P_{SN} was studied measuring carrier frequency offset nearby the threshold of self-excitation at RBW=100 kHz and the anode voltage by ≈150 V less than the threshold of self-excitation [7].

Smoothed by method of adjacent averaging, the offset traces vs. the injected resonant signal are shown in Fig 4.

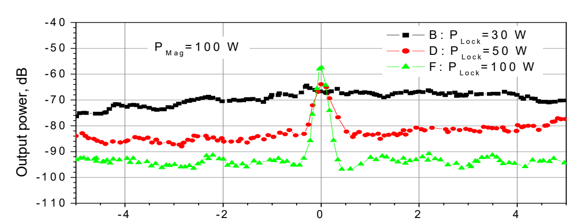

Figure 4: Smoothed offset of the carrier frequency of the 2M137-IL magnetron at the magnetron output power 100 W vs. power of the injection-locking signal, P_{Lock} [6].

The injected signal at P_{Lock} =30 W cannot launch the magnetron with this anode voltage. The trace shows the spontaneous oscillations caused by motion of charges in the interaction space and amplified by the resonant system

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of the magnetron. This trace indicates the wide-band oscillation in the interaction space at the bandwidth of ≈7 MHz at the level of -3 dB amplified by a resonant system up to ~1 W output power. One can infer that this trace shows the amplified spontaneous oscillations close to point of launching i.e., the quasi-continuous noise. Other traces show the incoherent spontaneous oscillations reduced due to their conversion by the phase grouping into the coherent generation when the magnetron is launched [6]. At P_{Lock} =100 W the spontaneous oscillations become mostly coherent one (phase-locked) due to the phase grouping. Its residual power P_{SN} characterizes the loss of coherency at the phase grouping vs. P_{Lock}.

STIMULATED RF GENERATION MODE FOR CW MAGNETRONS

We tested the Stimulated RF generation mode in pulse regime using type 2M219G CW, 2.45 GHz magnetron with nominal output power of 945 W and the self-excitation threshold of 3.69 kV [8]. The anode voltage was chosen to eliminate any start ups of the tube by noise or power supplies ripples. Solid lines in Fig. 5 show the ranges of magnetron power control vs. the magnetron anode voltage and the injected forcing signal power.

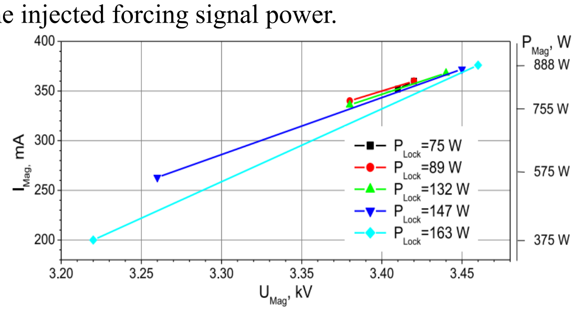

Figure 5: The ranges of the 2M219G magnetron anode voltage, the magnetron current and output RF power in the Stimulated RF generation mode at various power levels of the injected forcing signal P_{Lock} [8].

The efficiency $\eta \approx P_{RF}/(U_{Mag} \cdot I_{Mag} + P_{Lock})$ of the magnetron in the Stimulated RF generation mode, neglecting the filament power, is shown in Fig. 6. For the free running magnetron at the nominal power it is ≈54%.

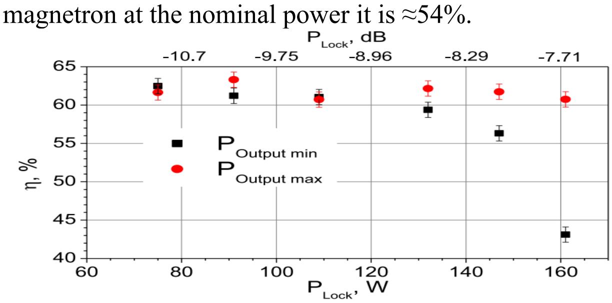

Figure 6: Dependence of conversion efficiency of the 2M219G magnetron on power of injected signal P_{Lock} [8].

The magnetron performs 100% pulse forced stimulated RF generation by injection of 100% pulse-modulated forcing signal, Fig. 7 at a DC feeding voltage.

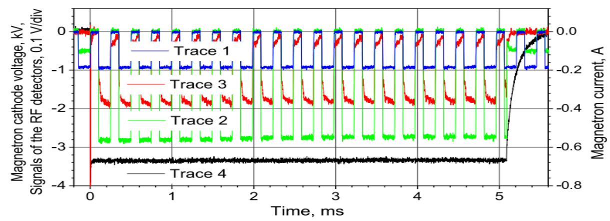

Figure 7: 4 kHz trains of 147 µs pulses (duty factor of ≈59%). Traces 1 and 2 - are the forcing injected and the output RF signals (powers of 125 W and 803 W, respectively); trace 3 - is the magnetron pulse current (right scale); trace 4 - is the tube cathode voltage (−3.37 kV).

There is no RF generation if the forcing signal is zero. The Stimulated RF generation mode is applicable for operation of CW magnetrons in pulse and CW regimes.

BANDWIDTH OF PHASE AND POWER CONTROL

The bandwidth of control of 2.45 GHz, 1 kW CW magnetrons BW_C measured by transfer functions magnitude and phase characteristics vs. P_{Lock} is shown in Fig. 8 [3].

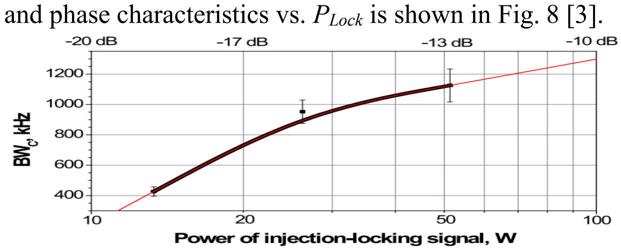

Figure 8: The admissible bandwidth of control of 2.45 GHz CW magnetrons. The thin line shows extrapolation.

The plotted curves indicate that even for 650 MHz magnetron RF sources the bandwidth of control should be ~1 MHz at the injected forcing signal ~ -10 dBc. Estimates of the bandwidth of phase and power control necessary for suppression of microphonics in ADS 650 MHz, 1 GeV, SRF proton driver with the proton beams from 1 to 10 mA are presented in [6].

SUMMARY

The Stimulated RF generation mode provides stable coherent generation of the tubes fed below the Hartree voltage and being driven by ~ -10 dBc forcing signal and allows phase and wide-range power controls with highest efficiency. The quasi-continuous noise in this mode is suppressed.

The pulse operation of magnetrons with 100% pulse modulation of the forcing signal results in 100% pulse modulation of output power without pulse modulators.

The phase and power control band of CW magnetrons operating in the Stimulated generation mode is widest and most suitable for various SRF accelerators.

The two-stage magnetron RF sources reduce the forcing signal to ≈ -20 dBc. In mass production of such RF sources their cost should much less than cost of traditional RF sources.

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