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Forced RF generation of CW magnetrons for superconducting accelerators

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Abstract

CW magnetrons, designed and optimized for industrial RF heaters, were suggested to power Superconducting RF cavities due to their higher efficiency and lower cost than traditional klystrons, IOT's, or solid-state amplifiers. RF amplifiers driven by a master-oscillator serve as coherent RF sources. CW magnetrons are regenerative RF generators with a huge regenerative gain. Very large regenerative gain causes instability with intense noise when a magnetron operates with the anode voltage higher than the threshold of self-excitation. Traditionally for stabilization of magnetrons is used injection-locking by a quite small signal. In this case the CW magnetrons do not provide correlation of the magnetron startup with the injection-locking signal. Thus, the magnetron except the injection locked oscillations may generate large noise. This may increase emittance of the beam in SRF accelerators. Recently we have developed mode for forced RF generation of CW magnetrons when the magnetron startup is provided by the injected forcing signal and the regenerative noise is suppressed. The mode is most suitable for SRF accelerators. The mode is briefly described below.

Key words: Superconducting RF accelerator, injection-locking signal, microphonics, ADS facility, beam emittance.

1. Introduction

The CW magnetrons, designed and optimized for industrial RF heaters, but driven by an injection-locking signal, were suggested in number of works to power Superconducting RF (SRF) cavities in accelerators due to higher efficiency and significantly lower cost of generated RF power per Watt than traditionally used RF amplifiers (klystrons, IOT's, 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 regenerative noise. Traditionally the magnetrons operate in the self-excitation mode (i.e. with the anode voltage above the self-excitation threshold) with a small injection-locking signal, P_{Lock} ~ -20 dB (or less) of the magnetron power P_{Mag}. In this case the regenerative noise of a CW magnetron destroys a necessary correlation of the tube startup with its injection-locking, i.e., the magnetron may be launched by the noise, but not by the injection-locking signal. Such probability is considered in the presented work. A developed method of forced RF generation CW magnetrons eliminating startup by noise and PS ripples is briefly described below. The method was verified in experiments with CW magnetrons for microwave ovens.

2. Operation of a CW injection-locked magnetron in a self-excitation mode

We consider operation of a CW magnetron as it is traditionally assumed, in a self-excitation mode, at a low injection-locked signal with 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 free running 2.45 GHz, 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.

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

$$w_{Lock} \sim \frac{\Delta f}{\Delta f_{FR}}. \quad (2)$$

$$w_{FR} \sim \frac{\Delta f_{FR} - \Delta f}{\Delta f_{FR}}. \quad (3)$$

The probabilities values 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 quite low, notably less than probability of the free running generation caused by noise. The noise oscillations are much less in magnitude than the injection-locked those. This leads to an intense quasi-continuous noise spectrum which is a disadvantage for operation of the self-exciting magnetrons with low

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locking signal for SRF accelerators. The distorted spectra of the RF sources with an intense quasi-continuous noise may preclude required suppression of microphonics and may increase emittance of the beam in SRF accelerators. Note, if the effective bandwidth of the injection-locking is approaches to zero, i.e., the transient time of the injection locking tends to infinity [1], then probability of the injection-locking also approaches to zero.

We have studied applicability of CW magnetrons for various projects of SRF accelerators. Experimental verifications were performed with 2.45 GHz microwave oven magnetrons. Figure 1, [3], shows measured spectral density of the noise power relatively the carrier frequency f_c of the magnetron type 2M137-IL operating above the self-excitation threshold voltage vs. the power of the injection-locking signal.

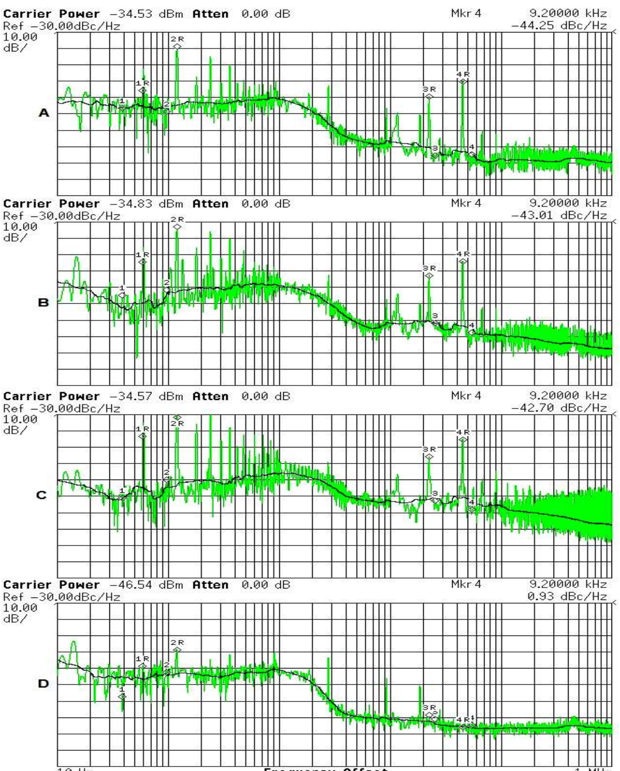

Fig. 1. The spectral power density of noise relatively f_c of the magnetron 2M137-IL at the output power of 1 kW, at the locking signal of 100, 30, and 10 W, traces A, B, and C, respectively. Traces D are the spectral power density of noise of the injection-locking signal (P_{Lock} =100 W), when the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

Measured in Fig. 1 a significant (by ~20 dBc/Hz) increase of the spectral density of noise power (f_{Lock} -f_0 >100 kHz) one can explain as quite narrow bandwidth of the injection-locking process and its low probability for the magnetron at the locking signal of -20 dB (10 W).

3. Operation of CW magnetron above and below the self-excitation threshold voltage

Measured with high bandwidth resolution, Fig. 2, clearly shows reduced quasi-continuous noise spectra (nearby f_c peak) of the magnetron type 2M137-IL when the magnetron operates below the self-excitation threshold voltage.

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 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 magnetron anode voltages U_{Mag} in this experiment were 3.90, 4.01 and 4.09 kV, respectively, [3].

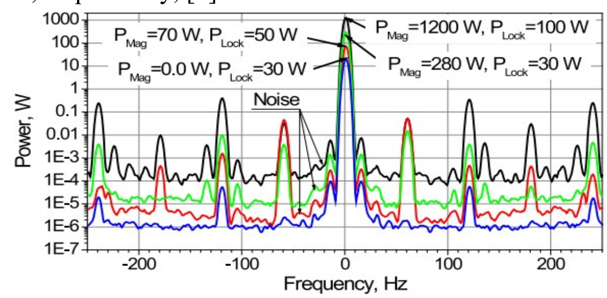

Fig. 2. Offset of the carrier frequency of the magnetron type 2M137-IL (operating in CW mode) with the threshold of self-excitation of 4.04 kV at various power levels of magnetron output, P_{Mag}, and the injection-locking signal, P_{Lock}.

Traces in Fig. 2 show that the ratio of magnetron output power to noise is larger for the operation below the self-excitation threshold voltage. For SRF accelerators one needs usage operation at highest ratio signal to noise, i.e., operation below the self-excitation threshold voltage with a quite large resonant injected signal (of about -10 dB).

Nearby the carrier frequency peak, Fig. 2, introducing dependence on the magnetron anode voltage, one can get graphs in Fig. 3 showing the regenerative noise with power P_{RN}, added to signal with magnitude P_{RS}, [4]. The last one characterizes incoherent oscillations in the space of interaction, entering the tube resonant system via the coupling slits [4]. The dots in Fig. 3 show plotted values of the total noise power P_{RN} + P_{RS} and the magnetron output RF power P_{Mag} vs. the magnetron voltage, U_{Mag} [4]. It is clearly seen that reducing the magnetron anode voltage allows significantly reduce the tube total noise.

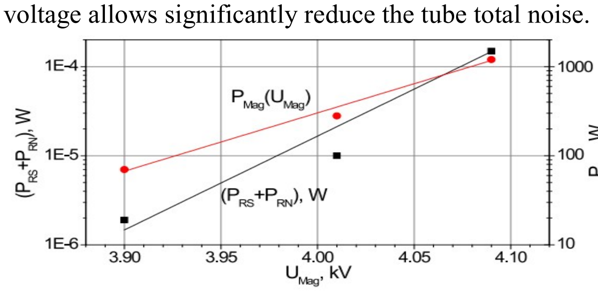

Fig. 3. Dependences of the magnetron total noise power (black dots, left scale) and the output power (red dots, right scale) vs. the anode voltage. Solid lines show the exponential fits of build-ups of the output power, P_{Mag} and P_{RS}+P_{RN} power for the magnetron 2M137-IL [4].

4. Stimulated generation mode of a CW magnetron

We have developed the Stimulated generation mode and tested it experimentally in pulse regime using a CW 2.45 GHz magnetron type 2M219G with nominal output power of 945 W and the measured magnetron self-excitation threshold voltage of 3.69 kV [5]. The mode uses operation of a magnetron below the threshold of self-excitation, with quite large injected forcing signal, but the anode voltage is chosen to eliminate any startups of the tube by noise or power supply ripples. Main characteristics of this mode are briefly presented below.

Solid lines in Fig. 4 show the ranges of power control in the CW magnetron vs. the magnetron anode voltage and the injected resonant signal power. The magnetron was powered by a pulse High Voltage (HV) source using a partial discharge of the 200 μF storage capacitor, [6], providing pulse duration of ≈5 ms. The pulsed HV source was powered by a charging Glassman 10 kV, 100 mA switching power supply allowing for voltage control.

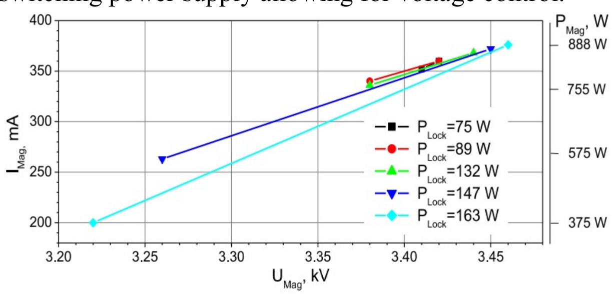

Fig. 4. The ranges of the 2M219G magnetron anode voltage and the magnetron current in the Stimulated generation mode at various power levels of the injected resonant signal P_{Lock}. The right scale shows measured RF output power of the magnetron corresponding to the magnetron current, I_{Mag} [5].

As it follows from Fig. 4, the injected resonant signal of -7.6 dB (163 W) allows the range of the magnetron power control of ≈ 3.7 dB by variation of the magnetron current in this tube. An increase of the range of the tube power (current) control is caused by larger coherent gain [4], due to improved phase grouping in the space of interaction for charges moving in spokes at larger injected resonant forcing signal.

The magnetron performs pulse forced Stimulated RF generation by the injection of a pulse forcing resonant signal into the magnetron RF system Figs. 5, 6.

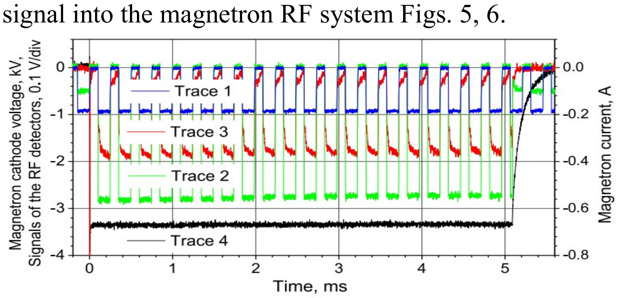

Fig. 5. 4 kHz trains of 147 μs pulses (duty factor of ≈59%). Traces 1 and 2 — the resonant injected and the magnetron output RF signals with powers of 125 W and 803 W, respectively; trace 3 — the magnetron pulse current (right scale); trace 4 — the magnetron cathode voltage (−3.37 kV). The magnetron pulse current was measured by a current transducer (type LA 55-P) with a circuit integration time ≈50 μs.

Despite the significantly lower regenerative gain at a reduced anode voltage, the magnetron in the Stimulated generation mode with a large forcing signal converts the spontaneous oscillations in the interaction space mainly into coherent ones [4], which are amplified by the resonant system of the tube. This provides almost rated output coherent RF power at the large coherent gain [4].

The absence of noise in the absence of a forcing resonant injected signal at the Stimulated generation mode is represented by the traces in Figs. 5 and 6 [5].

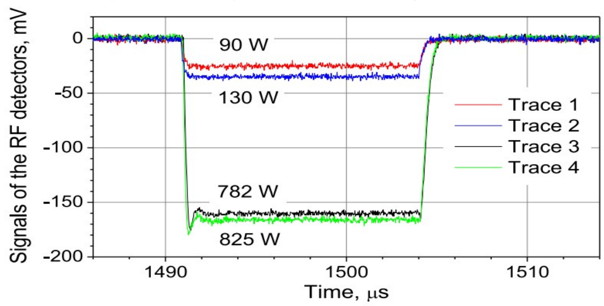

Fig. 6. Measured pulses of the 13 μs 20 kHz train when the magnetron operates in the Stimulated generation mode. Traces 3 and 4 are the magnetron output RF signals in dependence on the power of driving signals shown in traces 1 and 2, respectively.

The conversion efficiency *η*, expressed by the ratio of the generated RF power P_{RF} to the consumed power of a CW magnetron operating in the Stimulated generation mode, neglecting the filament power, is determined by the following expression:

$$\eta \approx P_{RF}/(U_{Mag} \cdot I_{Mag} + P_{Lock}) \quad (4)$$

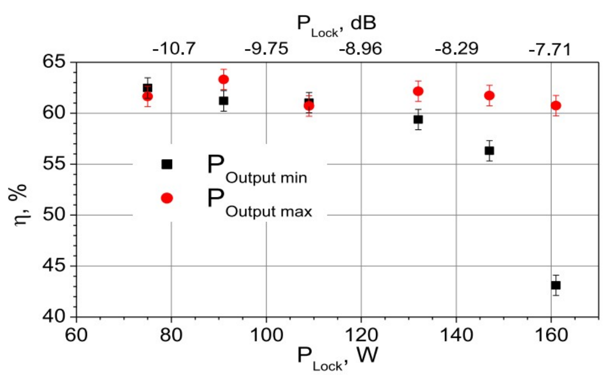

Fig. 7. Dependence of conversion efficiency of the 2M219G magnetron on power of injected signal P_{Lock}.

The plotted measured results relate to the maximum and minimum power of the magnetron operating in the Stimulated generation mode [5]. The measured conversion efficiency of magnetron operating above the self-excitation threshold in the ‘‘free run’’ mode (U_{Mag} ≈3.69 kV, P_{Lock} = 0) at the nominal tube power is ≈ 54%.

5. Bandwidth of phase and power control of magnetrons in Stimulated generation mode

For various SRF accelerator projects (colliders, ADS facilities and even industrial SRF accelerators is important wide-band control of SRF sources in phase and power for suppression various parasitic modulations (microphonics, etc). The Stimulated generation mode utilizes quite large injected resonant signal necessary for such control; it is most suitable for magnetron RF sources in SRF accelerators.

The bandwidth of control BW_C for 2.45 GHz microwave oven magnetrons obtained measuring the transfer functions magnitude and phase characteristics is presented in Fig. 9 [4].

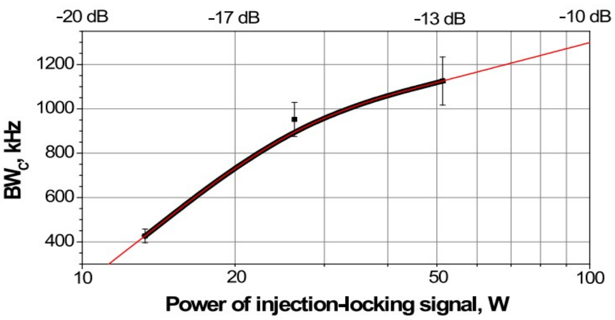

Fig. 9. The admissible bandwidth of control of 2.45 GHz microwave oven magnetrons determined by measured transfer functions characteristics. Black bold line shows the range and results of measurements with B-spline fit; the thin red line shows extrapolation.

The plotted curves indicate that even for 650 MHz magnetron RF sources the bandwidth of control should be ~1 MHz at quite large injected resonant signal.

Estimates of the bandwidth of phase and power control necessary for suppression of microphonics in ADS 1 GeV, SRF, 650 MHz proton driver with the proton beams from 1 to10 mA are presented in [4].

6. Summary

The measurements of the spectral density of noise power of CW magnetrons injection-locked by a low resonant signal and operating in the self-excitation mode indicates that the injection-locking bandwidth is narrow as it predicted by Adler theory. It means low probability of the injection-locked RF generation of the magnetron. In this case, the magnetron generates predominantly noise. Increasing the injection-locking signal to -10 dB reducing the noise power spectral density by ~20 dBc/Hz indicates a significant increase probability of the injection-locking at the -10 dB locking signal.

Measurements show that the noise (and the quasi-continuous noise spectra) are reduced in operation of the CW magnetrons below the threshold of self-excitation.

The developed Stimulated generation mode eliminates the CW magnetron noise out at the absence of the injected resonant signal. It means that magnetron in this mode generates practically the oscillations forced by the injected resonant signal, i.e., the forced coherent oscillations like traditional RF amplifiers.

Efficiency of CW magnetrons in the Stimulated generation mode is significantly higher than efficiency of the magnetron operating in self-excitation modes: free run or driven by a small injection-locking signal, see [2].

The Stimulated generation mode allows adjusting the magnetron power in a wide range, up to almost the nominal power of the tube.

The Stimulated generation mode is suitable for CW and pulse SRF accelerators. However, the High Voltage pulse modulators shaping pulse anode voltage of magnetrons no need when the Stimulated generation mode is used for pulse SRF accelerators. Stimulated generation mode provides 100% pulse modulation of the magnetron output power at 100% pulse modulation of the resonant injected signal.

The bandwidth of the phase and power control in CW magnetrons operating in the Stimulated generation mode is most suitable for suppression of parasitic modulations in the SRF cavities of accelerators.

A required injected resonant forcing signal necessary for the Stimulated generation mode one can obtain using two-cascade magnetrons [3]. This allows reduction of power of the injected resonant signal by ≈10 dB. The first CW magnetron with 10% power of the power required from the RF source provides the injected resonant signal for the second, high power CW magnetron. The power control is provided by regulation of the magnetron current in the high power tube. At the mass products the cost of both tubes will be increased very insignificantly.

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