CW magnetrons for superconducting accelerators. Suggestions and reality.

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On application of CW magnetrons for superconducting accelerators.

High power CW magnetrons, designed and optimized for industrial RF heaters, were suggested to power Superconducting RF cavities due to their higher efficiency and lower cost of RF power per Watt comparing to amplifiers (klystrons, IOTs, solid-state amplifiers).

RF amplifiers driven by a master oscillator serve as controllable coherent RF sources.

CW magnetrons are regenerative RF generators with a huge regenerative gain to start up reliably by noise even they are fed by DC HV power supplies.

Very large regenerative gain causes regenerative instability with a large noise when a CW 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 CW magnetrons do not provide correlation of the magnetron startup with the injected locking signal. Thus, the magnetron with the injection locked oscillations may generate large noise. This may preclude the required suppression of microphonics and will increase emittance of the beam in SRF accelerators.

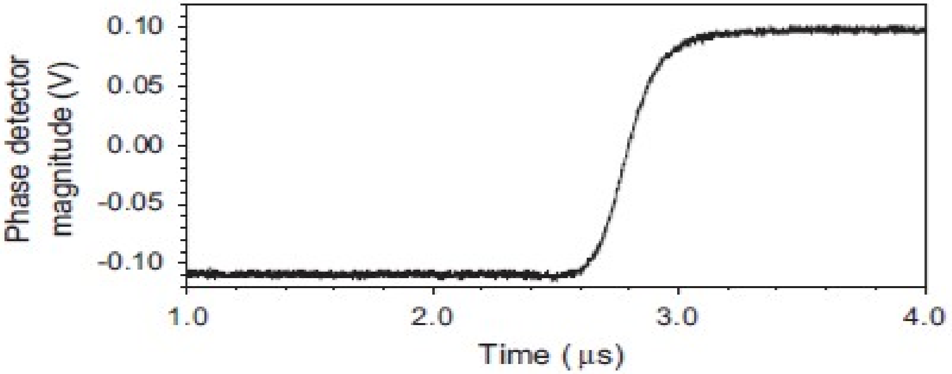
The theory of magnetrons operation presently does not exist. Phenomenological models of magnetrons start up and operation proposed 60–80 years ago generally relate to pulse magnetrons and cannot provide capabilities to choose the CW tubes operating parameters and design for application of the tubes in SRF accelerators

Typically, the CW magnetrons operate in the self-excitation mode, i.e., with the anode voltage above the self-excitation threshold and with a small injection-locking signal, $P_{Lock} \approx - 20$ dBc or less of the magnetron power P_{Mag}. In this case a CW magnetron may start RF generation by the regenerative noise or ripples of Power Supplies (PS), but not by the injection-locking signal.

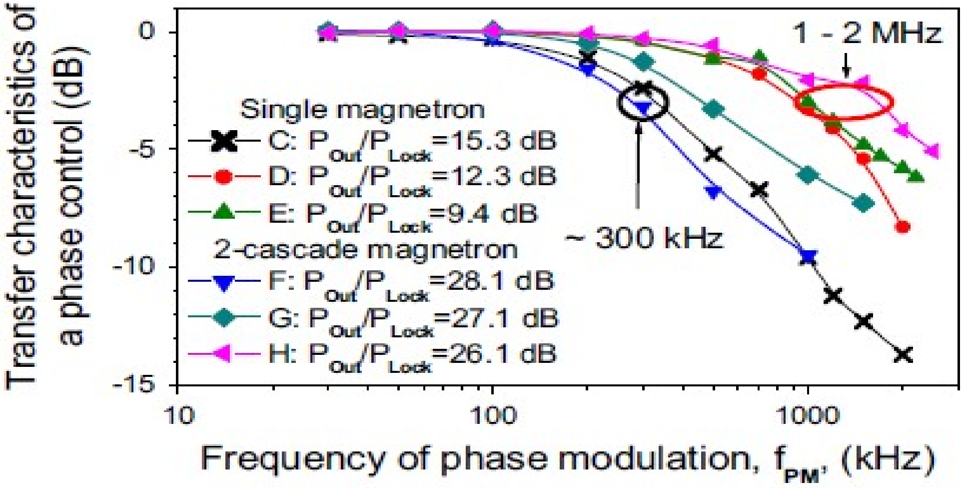
First results of study of CW magnetrons

The measurements and simulations were performed to understand the possibility of CW magnetrons to drive SRF cavities of Project X accelerator.

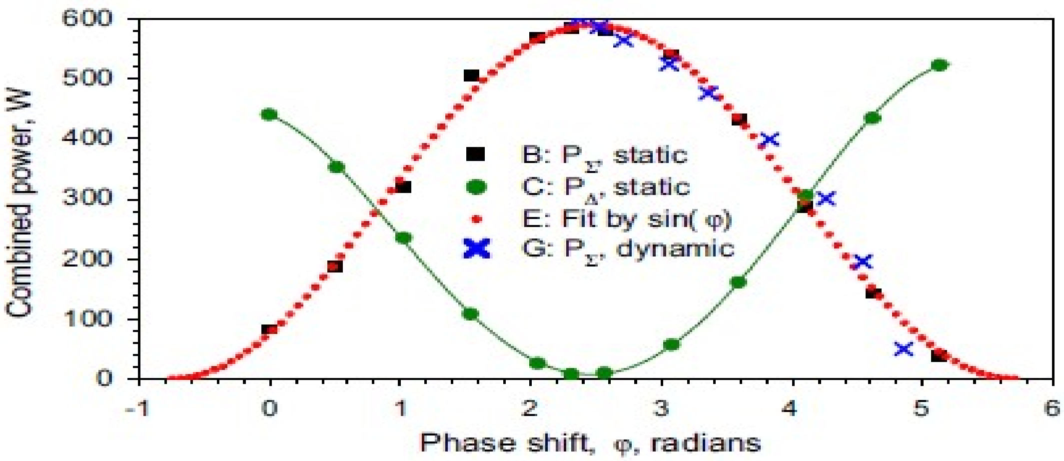
[G. Kazakevich et al., NIM A 760 (2014) 19-27].



Response of the injection-locked 2-cascade magnetron on the 180 deg. phase flip measured at ratio of the output power to locking power ≈27 dB; the phase detector calibration is ≈0.8 deg./mV.

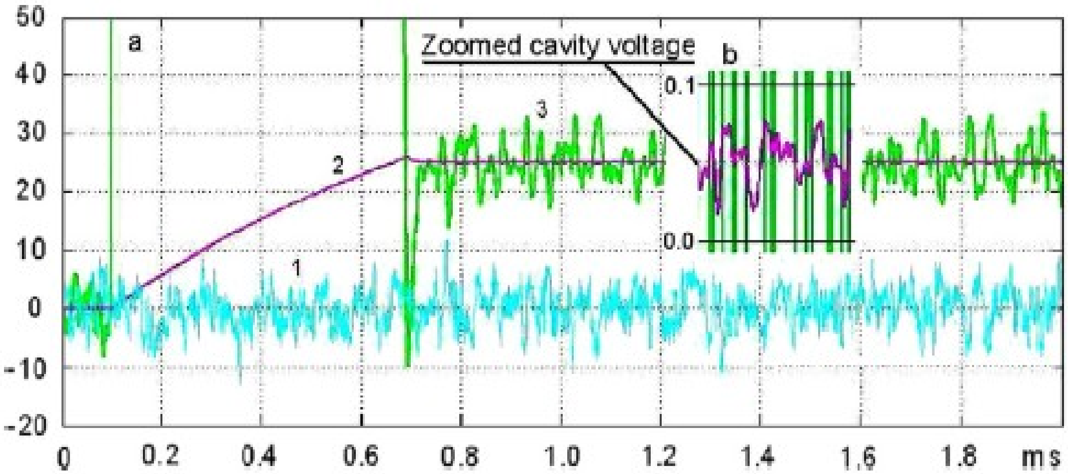


Transfer function magnitude characteristics (rms values) of the phase control measured in phase modulation domain with single and 2-cascade injection-locked magnetrons at various ratios P_{Out}/P_{Lock}, at P_{Out} =450 W.



Control of combined power of the 2-channel injection-locked magnetron by the phase difference. Dots B and C present power variation at the combiner ports Σ and Δ, respectively, measured in static regime. Dots G show power variation at the combiner port Σ measured in dynamic regime. Dots E show fit of the plots B and G by *sin(φ)* function.

[G. Kazakevich, TUDF1132. EIC 14, (2014).



a: Curve 1 shows the 400 kHz bandwidth disturbance; curve 2 shows cavity voltage; curve 3 shows RF drive. Vertical scale is 10 MV/div. Inset b presents zoomed in ≈300 times (in vertical) trace of the cavity voltage, curve 2, in time domain. Vertical scale in inset "b" is 0.1 MV/div.

Required Field Control to meet SRF accelerator performance

Required Field Control to meet accelerator performance:

– **Proton/ion Accelerators/Rings: 0.5 deg. and 0.5%**
– ***Nuclear Physics Accelerators: 0.1 deg. and 0.05%***
– ***Light Source: 0.01 deg. and 0.01%***

[C. Hovater, TUBF1131_TALK, EIC 14, 2014]

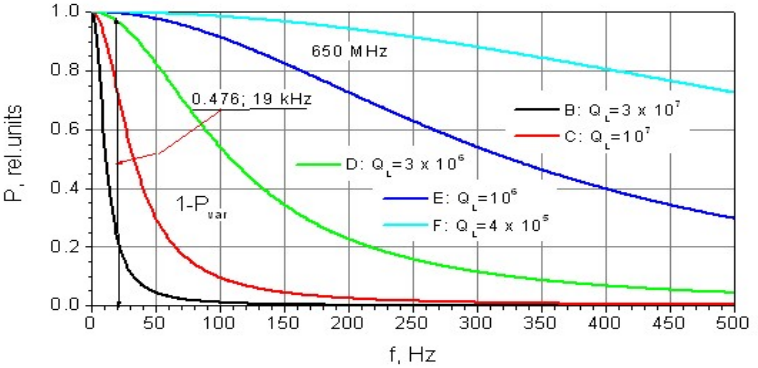
This may make it necessary to suppress parasitic modulation of the phase and power of the accelerating field in various SRF accelerator projects. Stabilization of phase was first realized in the following work:

[H. Wang, K. Davis and R. Rimmer, I. Tahir, A.C. Dexter, G. Burt and R.G. Carter, Proceed of IPAC10, pp. 4026-4028, Kyoto, Japan, 2010,]

For stabilization of the accelerating field in the SRF cavities in CW accelerators is used suppression of microphonics.

J.R. Delayen, Proceed. PAC 01, pp. 1146-1148, USA, Chicago, 2001.

On suppression of microphonics in Nuclear Physics Accelerators



For bandwidth control one needs use calculations of the SRF cavity resonant curve nearby the resonance.

[L.D. Landau and E.M. Lifshitz, *in course of* Theoretical Physics, V 1, Machanics, Chapter "The forced oscillations with friction", Elsevier, ISBN-13 9780750628969, 1982].

Using the admissible microphonics distortion of 0.05% one can estimate the range of amplitude modulation of electric field to suppress the microphonics as a value of R_C=[2x0.476/(0.05%)] ≈ 65.6 dB. The first-order filters used in the LLRF loops have out-of-band roll-off of 20 dB per decade, thus the bandwidth of the accelerating field amplitude control in Hz is: $B_C \geq R_C/20 \geq$38 kHz. For ADS proton accelerator with beam current of 1 mA the bandwidth has to be ≥ 3.8 kHz.

On a quite fast power control in magnetrons

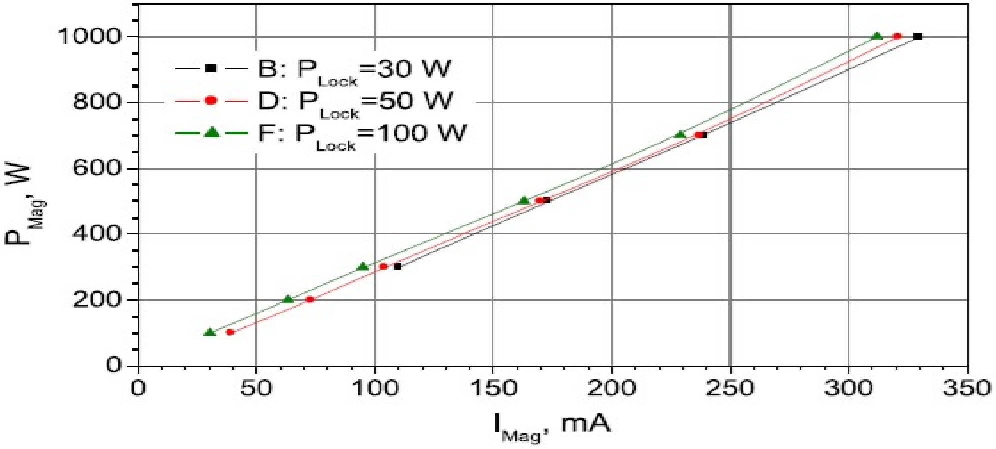
For a quite fast power control in magnetrons one can use two methods of vector control:

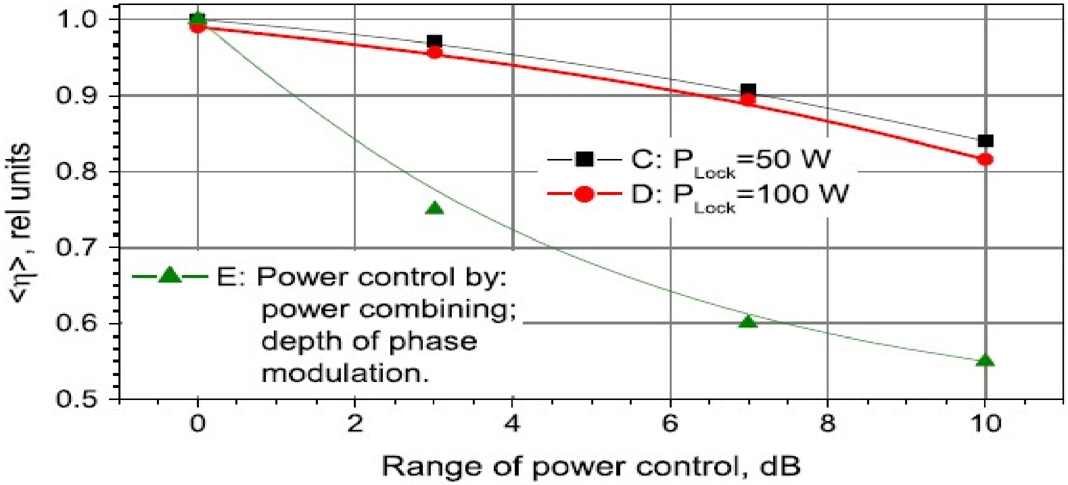
[G. Kazakevich et al., NIM A 760 (2014) 19-27].
[B. Chase, R. Paskuinell, E. Cullerton Varghese, JINST, V10, P03007 (2015)].

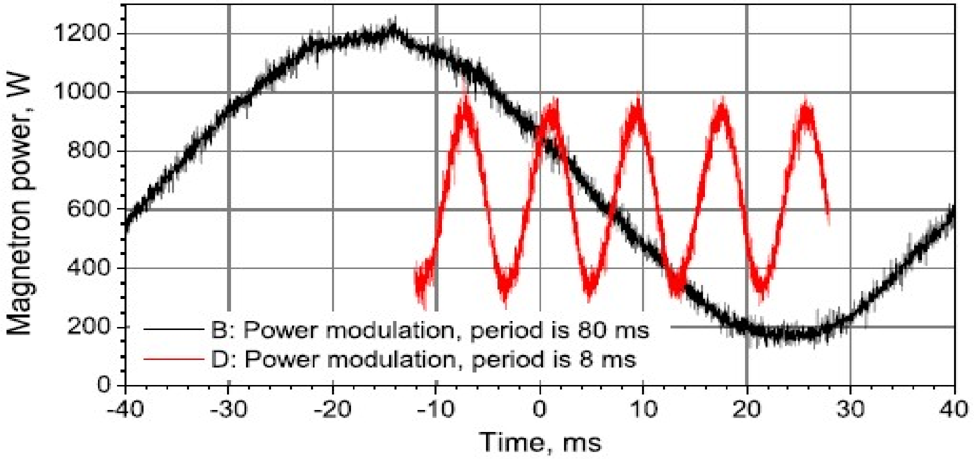
Test of the second method with 2.45 GHz SRF cavity demonstrated the rms phase and amplitude deviation of 0.26 deg. and 0.3%, respectively at 4 K.

More efficient method of power control uses regulation of the magnetron current. The range of power control may be ≥10 dB at the injected resonant signal of -10 dBc.
The magnetron output power P_{Mag} is linearly dependent on the magnetron current I_{Mag}.

[G. Kazakevich et al. NIM A 839 (2016) 43-51].





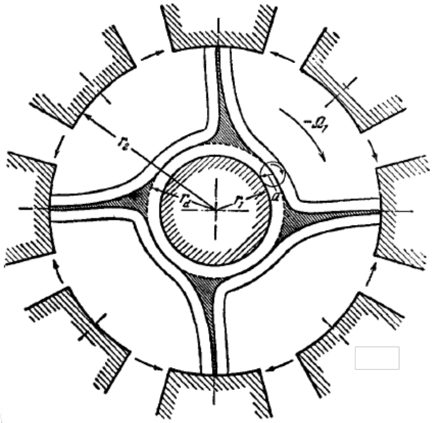


Modulation of the magnetron RF power performed controlling the magnetron current by the high voltage switching power supply at P_{Lock} =100 W.

Electrodynamic model of magnetrons operation and control

An analytical model of the resonant interaction of Larmor electrons (drifting in the crossed fields of a magnetron) with a synchronous wave providing a phase grouping of the drifting charges was developed to optimize the parameters of an RF resonant injected signal driving the magnetrons for control of phase and power of the RF sources with a rate required for SRF accelerators.

[G. Kazakevich et al., PRAB 21, 062001 (2018)].



The model is based on charge drift approximation for *N*-cavities magnetron, at magnetic field *H*, frequency ω, operating in π mode

[P. L. Kapitza, High power electronics, Sov. Phys. Usp. 5, 777 (1963)].

The final equations of the model in a polar frame are:

$$\varepsilon = \tilde{E}_n(r_1)/E_r(r_1) = \tilde{E}_n(r_1) \cdot r_1 \ln(r_2/r_1)/U.$$

$$\begin{cases} \dot{r} = \omega \frac{r_S^2}{r} \varepsilon \phi_1(r) \cos(n\varphi_S) \\ n\dot{\varphi}_S = -\omega \frac{r_S^2}{r} \left(\frac{d\phi_0}{dr} + \varepsilon \frac{d\phi_1}{dr} \sin(n\varphi_S) \right) \end{cases}$$

, here: $r_S = \sqrt{-ncU/[\omega H \ln(r_2/r_1)]}$, $n = N/2$,

$$\phi_0(r) = \ln\frac{r}{r_1} - \frac{1}{2}\left(\frac{r}{r_S}\right)^2 \quad \text{and} \quad \phi_1(r) = \frac{1}{2n}\left[\left(\frac{r}{r_1}\right)^n - \left(\frac{r_1}{r}\right)^n\right],$$

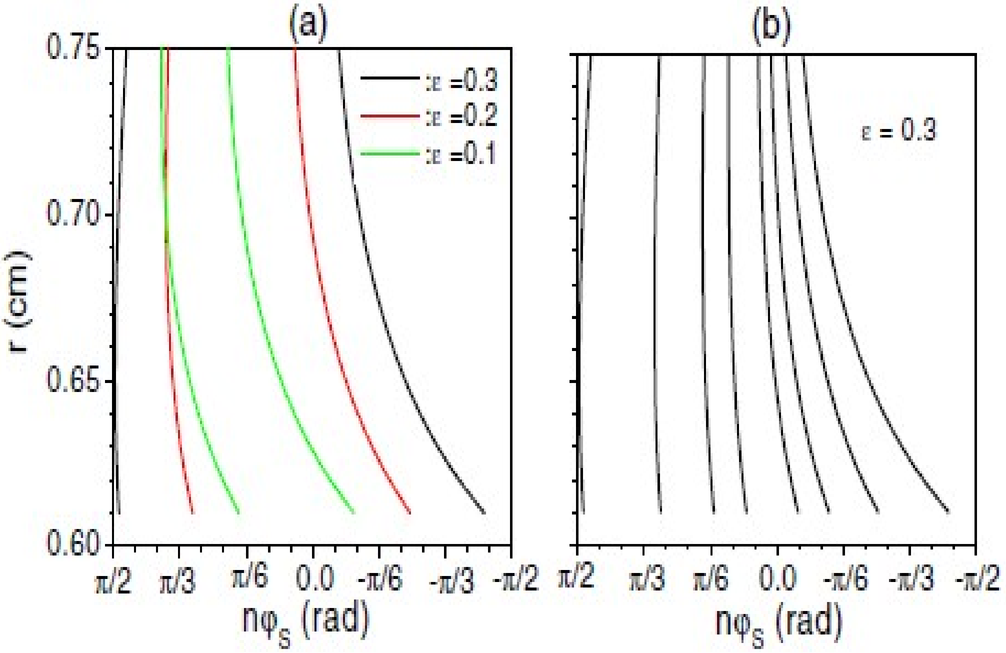
L. A. Vainstein and V. A. Solntsev, in Lectures on microwave electronics, Moscow, Sov. Radio, 1973 (in Russian).

The top equation describes the radial velocity of the moving charge. In accordance with this equation, the drift of the charge towards the anode is possible at $-\pi/2 < n\varphi_S < \pi/2$ with a period of 2π, i.e., only in “spokes.” The charge can enter the spoke through the boundaries located at $\pm\pi/2$. The radial drift velocity is proportional to the synchronous wave magnitude, ε. The condition $\varepsilon \geq 1$ does not allow operation of the magnetron. The second equation describes the azimuthal velocity of the drifting charge in the frame of the synchronous wave. The second term in the parentheses causes phase grouping of the charge by the resonant RF field via the potential ϕ_1.

The first term of this equation describes a radially dependent azimuthal drift of charge, resulting from the rotating frame, with azimuthal angular velocity $-\omega/n$.

Equations were numerically integrated for a typical model of a commercial magnetron with N = 8, r_1=5 mm, r_2/r_1=1.5, r_S/r_1= 1.2. Considering the charge drifting in the center of the Larmor orbit, we obtained the charge trajectories at $r \geq r_1 + r_L$ for various magnitudes ε of the RF field in the synchronous wave, and during the time interval of the drift of $2 \leq \tau \leq 10$ cyclotron periods allowing coherent contribution to the synchronous wave.

[G. Kazakevitch et al., PRAB, 21, 062001 (2018)]



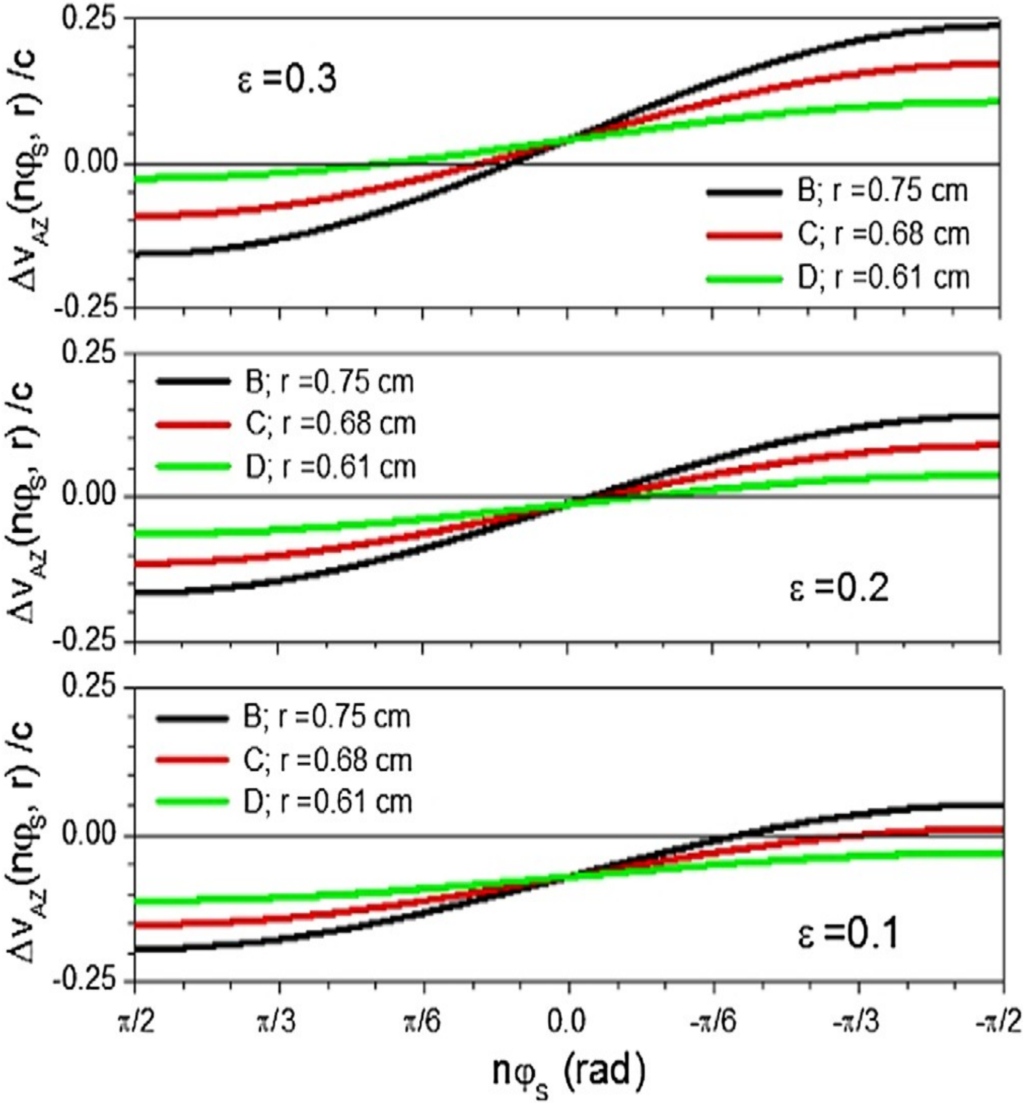
Graph (a) shows the phase boundaries of trajectories of the charges contributing to the synchronous wave in dependence on ε. Graph (b) shows trajectories of the charges in a spoke at ε =0.3.

In the frame of the slow synchronous wave the RF azimuthal electric field in a spoke can be considered as stationary. The electric field strongly coupled with the resonant mode of the magnetron oscillation acts as a stationary field on the charge drifting in the spoke. This causes the resonant energy exchange between the synchronous wave and the charge. If the azimuthal velocity of the drifting charge is a bit greater than the azimuthal velocity of the synchronous wave, the charge induces oscillation of the resonant mode in the magnetron RF system and contributes to the synchronous wave being decelerated.

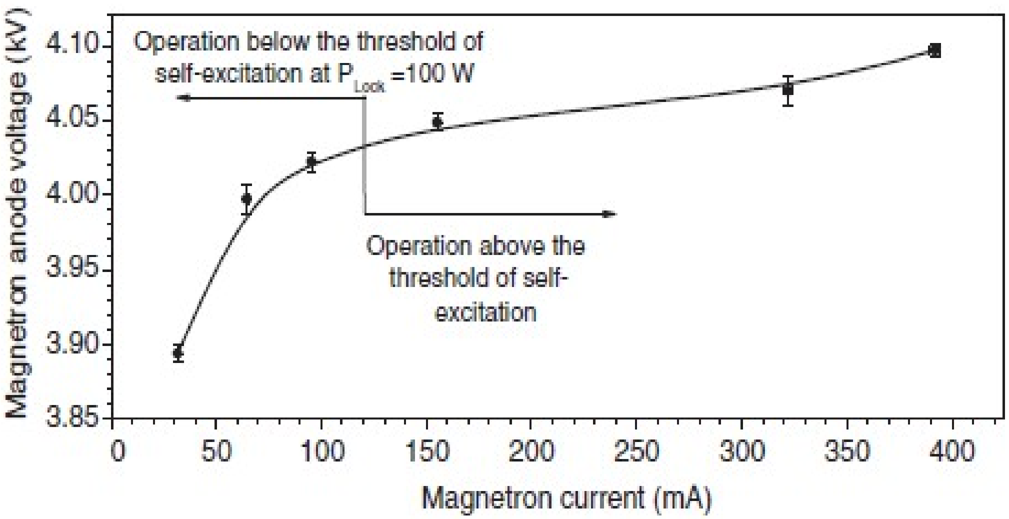
This increases the amplitudes of the synchronous wave and the RF field in a magnetron RF system. The energy exchange of a drifting charge with a synchronous wave causes a variation of the azimuthal velocity of the drifting charge, ensuring the phase grouping.

The increase or decrease of the self-consistent electric field of the synchronous wave can be determined by the difference in the azimuthal velocities of the drifting charge and the synchronous wave $\Delta v_{AZ}(n\varphi_S, r)$ calculated for the drift.

Thus, the energy decrement or the increment in the synchronous wave are determined by the sign of the $\Delta v_{AZ}(n\varphi_S, r)$ quantity, and one can estimate the value of ε necessary and sufficient for the coherent generation of the magnetron by integration of $v_{AZ}(n\varphi_S, r)$ over the entire phase interval admissible for a spoke. Positive values of the integrals of $v_{AZ}(n\varphi_S, r)$ indicate that the RF energy added into the synchronous wave by the drifting charges is larger than the energy removed from the synchronous wave at the phase grouping of the charges.



Thus, for ε =0.3 (corresponding P_{Lock} ≅ -10 dBc) one can expect stable operation of a magnetron below the self-excitation threshold voltage. This strongly changes regulations of usage of CW magnetrons for SRF accelerators.



Magnetron V-I characteristic measured at P_{Lock} =100 W. The solid line (B-spline fit) shows the available range of current with stable operation of the tube at power of the resonant injected signal P_{Lock} = 100 W. The magnetron was 2M137-IL.

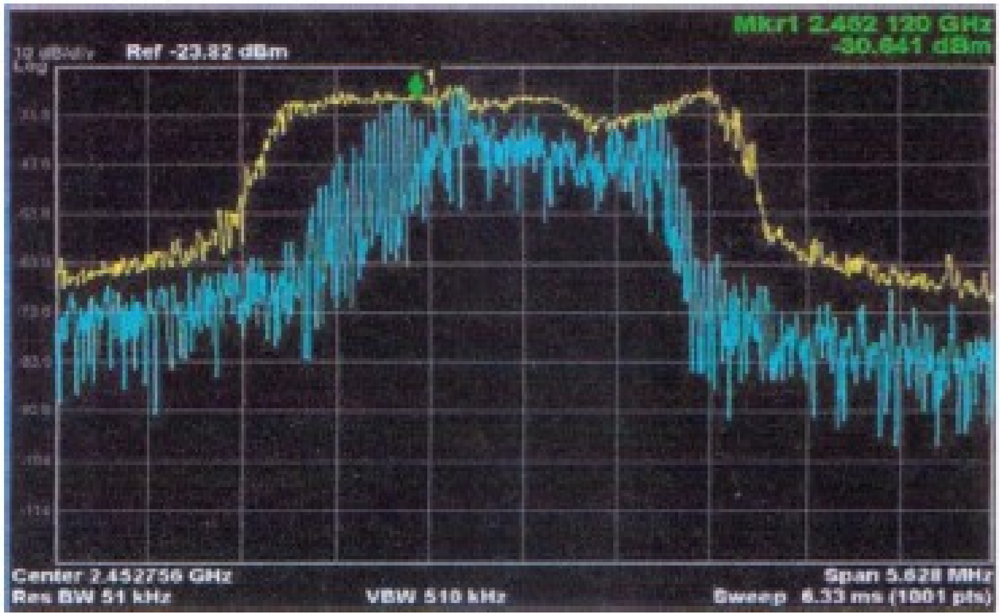
On probability of the injection locking

We considered operation of a CW magnetron as it is traditionally assumed, in a self-excitation mode, at a free run or with injection-locked signal at power P_{Lock}. The effective bandwidth of injection-locking, Δf at the locking signal with power P_{Lock} is expressed by the following equation: $\Delta f = \frac{f_0}{2Q_L}\sqrt{\frac{P_{Lock}}{P_{Mag}}}$.

[A.C. Dexter, WEIOA04 in Proceed. of LINAC2014, Geneva, Switzerland, (2014)].

For the free running 2.45 GHz, microwave oven CW magnetron type 2M137-IL the effective bandwidth Δf_{FR}~4.5 MHz.

[R.J. Paskuinelli, RF Sources, PIPII XMAS, Feb. 26, 2014].



For 2.45 GHz CW tube one estimates as:

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

The probabilities estimated values 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

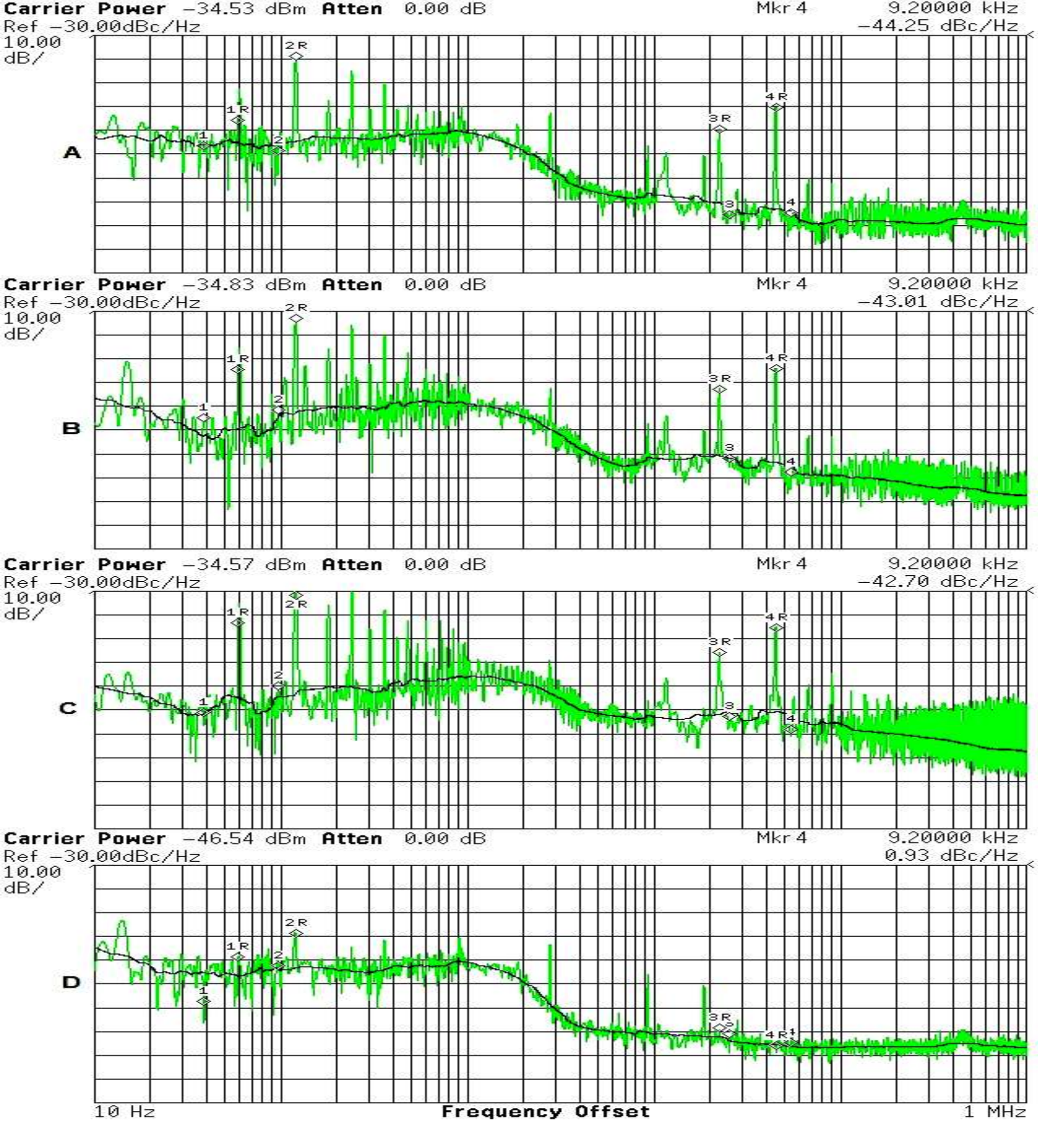
Probability of the injection-locked RF generation of such RF source may be notably less than probability of the free running generation caused by noise.

[G. Kazakevich et al, FERMILAB-PUB-23-663-TD-V]

This was tested by measuring the spectral density of the noise power.

[G. Kazakevich et al, PRAB, 21, 062001 (2018)]

Spectral density of noise power vs. P_{Lock}

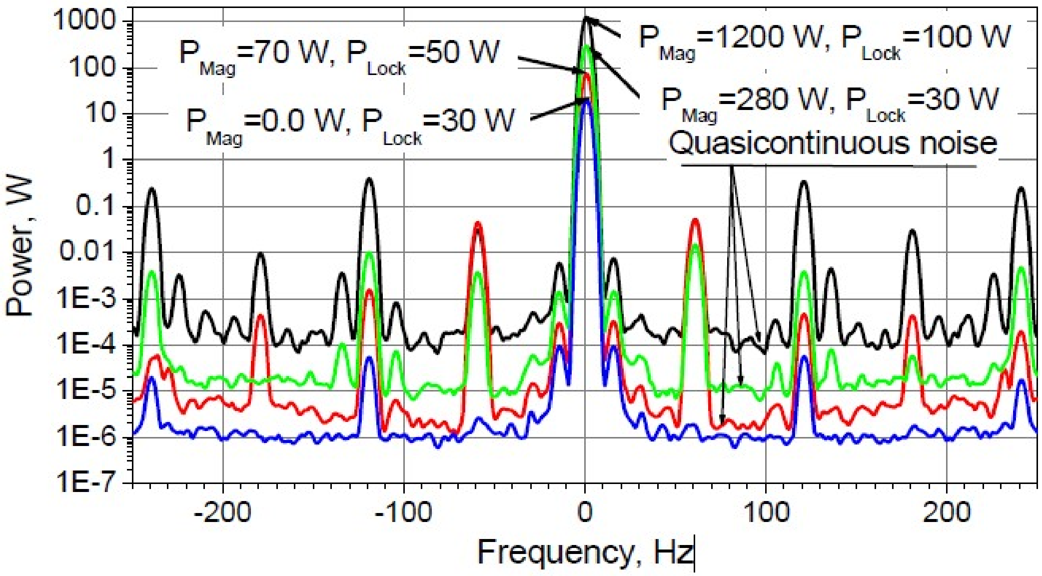


The spectral density of noise power of the magnetron 2M137-IL at the output power of 1 kW, at the locking signal of 100, 30, and 10 W, traces A, B, and C, respectively. Traces D are the spectral density of noise power of the injection-locking signal (P_{Lock} =100 W), when the magnetron feeding voltage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

[G. Kazakevich et al, PRAB, 21, 062001 (2018)]

The plots show increase of the spectral density noise power by ≈20 dBc/Hz at P_{Lock} =10 W in the frequency offset range 0.1-1 MHz. This indicates low probability of the injection-locking process at low P_{Lock}, with noise resulting from incoherent generation.

Operation of magnetron above and below the self-excitation.

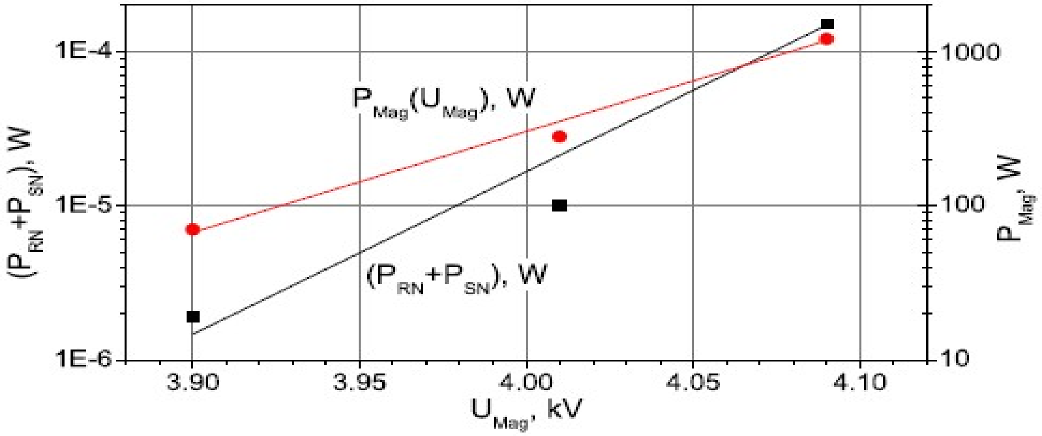


Offset of the carrier frequency of the magnetron 2M137-IL (operating in CW mode) with the threshold of self-excitation of 4.04 kV at various power levels of magnetron output, P_{Mag}, and the injection-locking signal, P_{Lock}.

[G. Kazakevich et al. NIM A 839 (2016) 43-51].

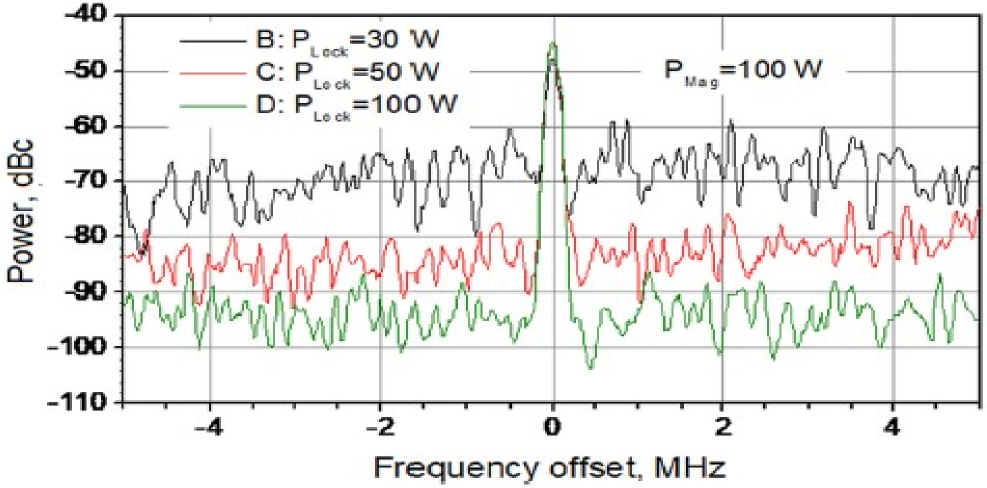
The ratio P_{Mag} */power of quasi-continuous noise* is increased when the tube operates below the self-excitation threshold.

On forced RF generation of CW magnetrons



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 fits of build-ups of the output power, P_{Mag}, and $P_{SN}+P_{RN}$ power for the magnetron 2M137-IL. P_{RN} is a regenerative noise, P_{SN} characterizes incoherent spontaneous oscillations in the interaction space depending on the U_{Mag}.

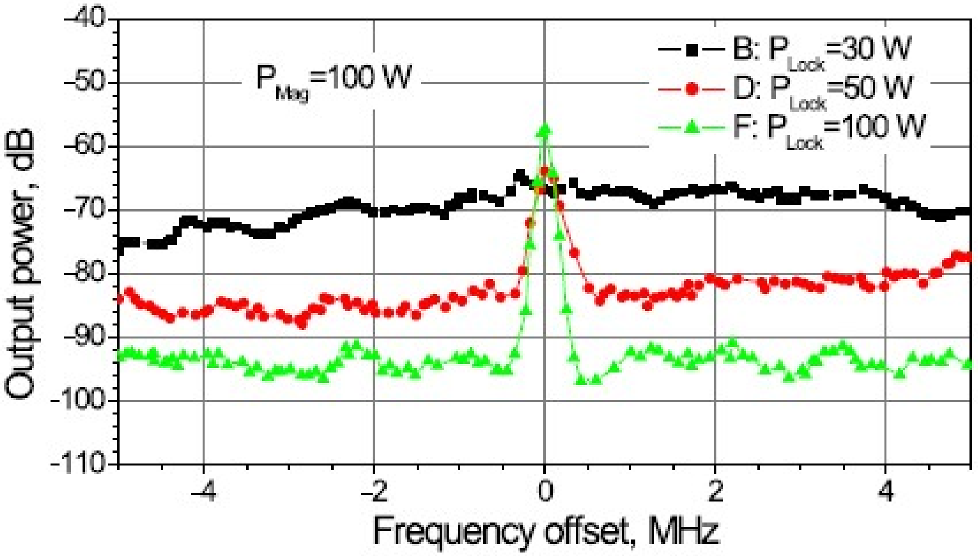
[G. Kazakevich et al. NIM A 1039 (2022) 167086]



Offset of the carrier frequency of the magnetron type 2M137-IL measured at the magnetron output power 100 W, Ref - 45 dBc, vs. power of the injection-locking signal, P_{Lock}.

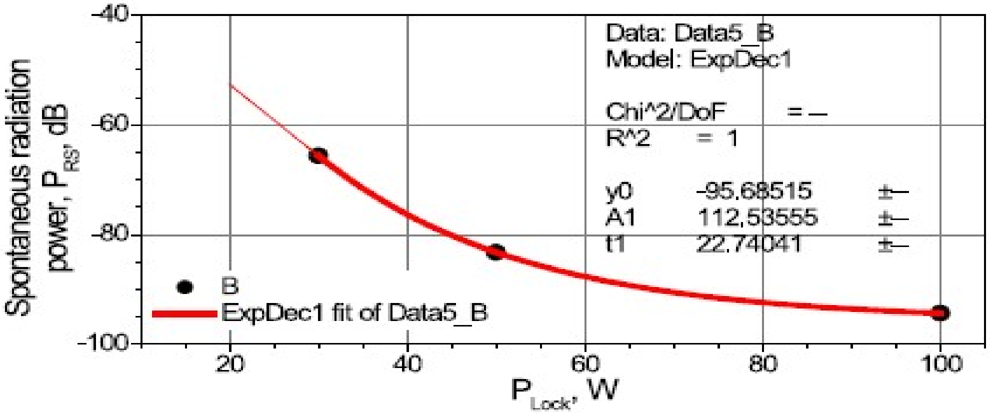
[G. Kazakevich et al. NIM A 839 (2016) 43-51].

Smoothed offset of RF generation by the adjacent averaging method.



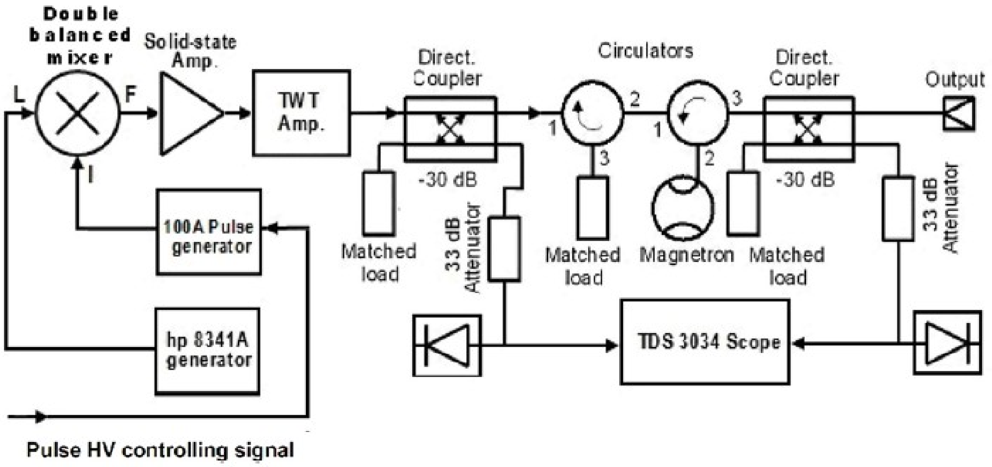
Smoothed offset of the carrier frequency of the 2M137-IL magnetron at the output power of 100 W vs. power of the injection-locking signal, P_{lock}.

[G. Kazakevich et al, NIM A 1039 (2022) 167086].



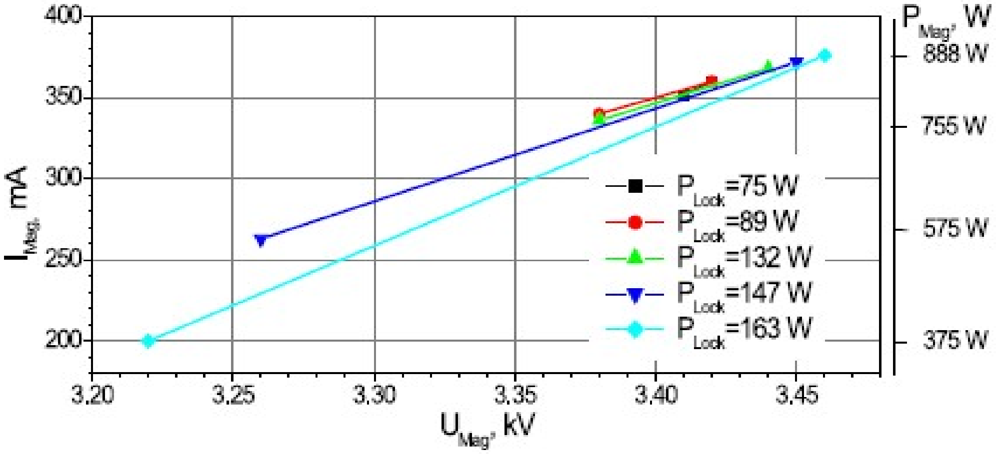
Fitting the power of the smoothed spontaneous radiation, shown by dots, by exponential decay vs. power of the injection-locking signal P_{Lock}, bold line; the thin line shows the extrapolation {Ibid.}.

Stimulated RF generation of CW magnetrons

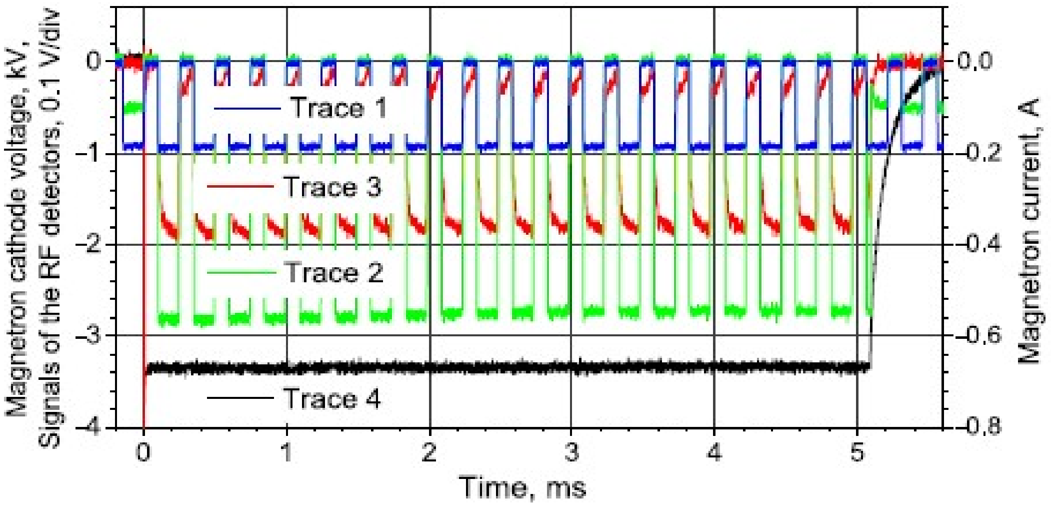


Setup to study pulse control of the magnetron type 2M219G driven by a gated injected forcing signal. A CW forcing signal from RF generator type HP 8341A controlling the magnetron was gated by the double balance mixer ZEM-4300MH (from Mini-Circuits) controlled by the pulse generator type 100A.

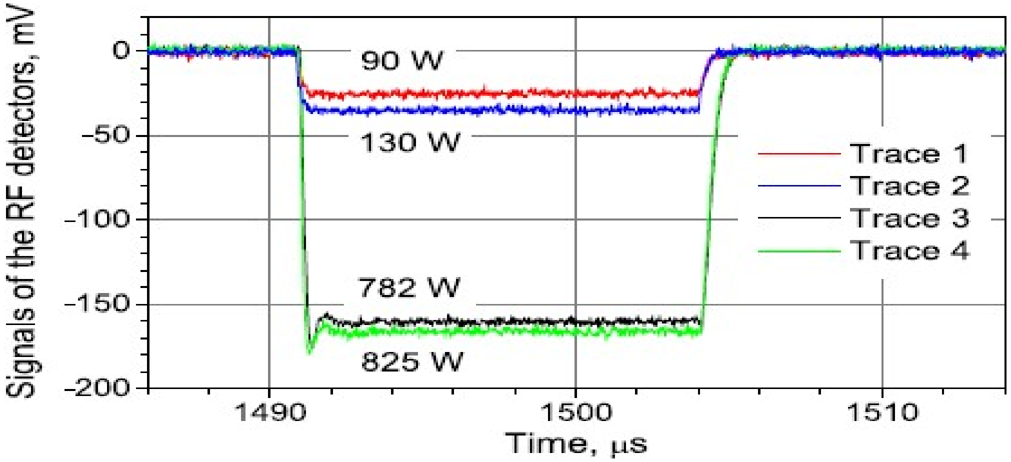
G. Kazakevich et al, NIM A 980 (2020) 164366.



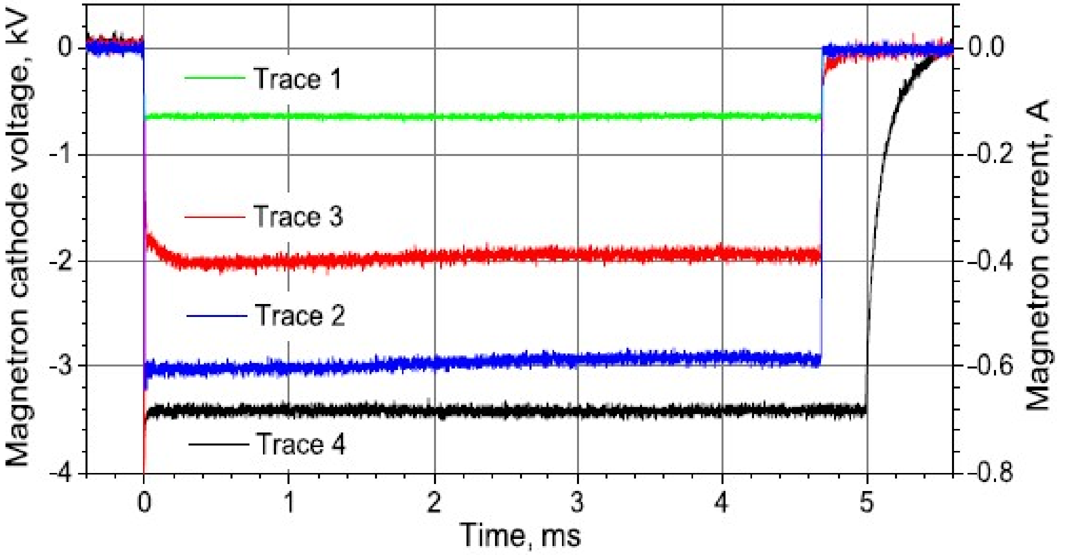
Measured ranges of the anode voltage, U_{Mag}, and the magnetron current, I_{Mag}, in the Stimulated RF generation mode for a 2.45 GHz, 945 W magnetron type 2M219G (the threshold voltage of the self-excitation is 3.69 kV) at various power levels of the injection-locking signal P_{Lock}. The right scale shows measured RF power of the magnetron, P_{Mag}, vs. the magnetron current, I_{Mag}.



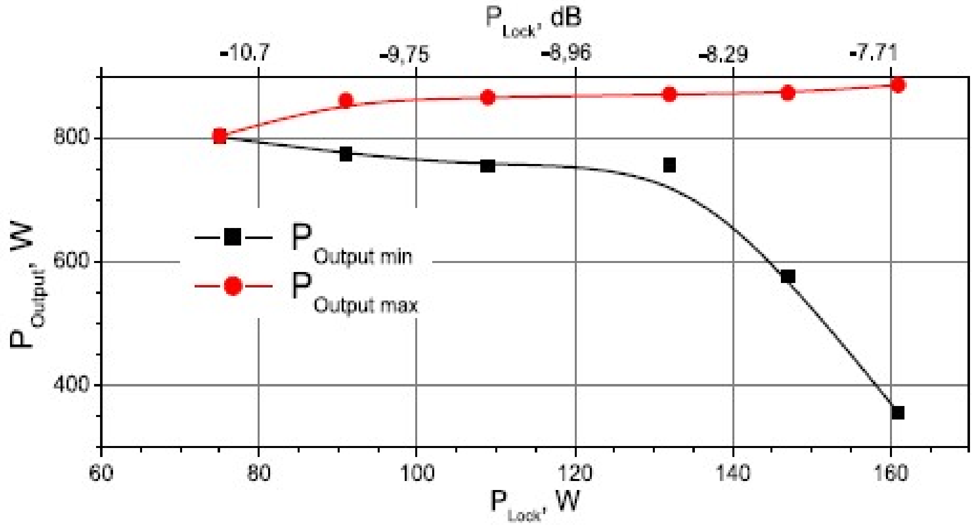
4 kHz trains of 147 μs pulses (duty factor of ≈59%). Traces 1 and 2 – are the resonant forcing and the magnetron output RF signals with powers of 125 W and 803 W, respectively; trace 3 - is the magnetron pulse current (right scale); trace 4 - is the magnetron cathode voltage (- 3.37 kV). The magnetron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



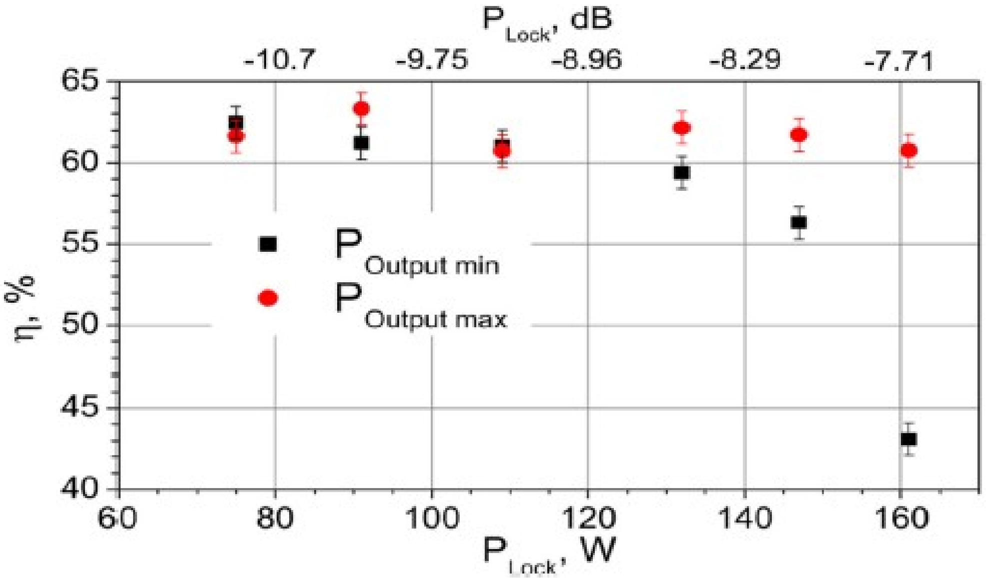
Measured pulses of the 13 μs, 20 kHz train when the magnetron operates in the Stimulated RF generation mode.



Operation of the magnetron in the stimulated mode of pulsed generation with pulse duration of 4.7 ms. Traces 1 and 2 — the resonant injected and the magnetron output RF signals with powers of 74 W and 888 W, respectively; trace 3 — the magnetron pulsed current (right scale); trace 4 — the magnetron cathode voltage (−3.43 kV).

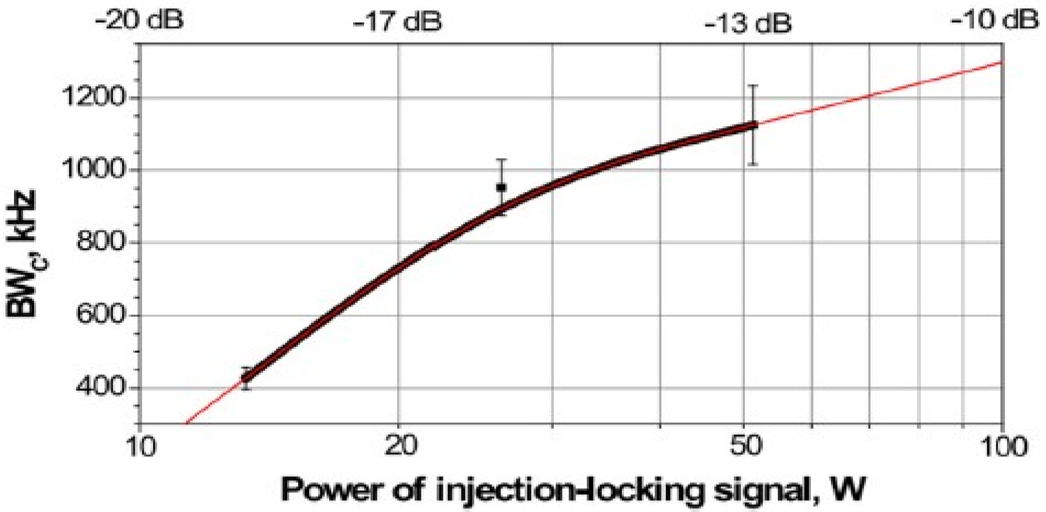


Measured ranges of the magnetron 2M219G output power vs. power of the forcing signal.



Efficiency of the magnetron 2M219G vs. power of forcing signal P_{Lock}. The magnetron efficiency in Free Run mode is 54%.

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



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.

Summary

- ***Recently developed and tested by CW magnetrons the Stimulated RF generation mode is suitable for pulse and CW operation.***
- ***The Stimulated RF generation mode provides highly-stable coherent generation of the tubes fed below the Hartree voltage and being driven by the forcing signal of ~ -10 dBc.***
- ***The quasicontinuous noise in this mode is practically suppressed.***
- ***Pulse operation of CW magnetrons with 100% pulse modulation of the forcing signal results in 100% pulse modulation of the tube output power in this mode without HV pulse modulators.***
- ***One can reduce the forcing signal by ~10 dB using two-cascade magnetron; both work in the Stimulated mode. The first tube with power ~10% of the maximum required power amplifies the forcing signal, the second high-power tube may regulate the output power.***
- ***Bandwidth of phase and power control of CW magnetrons operating in the Stimulated RF generation mode is most wide and most suitable for various SRF accelerators.***
- ***Lover the magnetrons anode voltage and reduced the electron back-stream in the Stimulated RF generation mode along with improved tubes vacuum will increase the magnetrons life time.***