Physics of magnetrons at a control for superconducting accelerators

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High-power electro-vacuum RF sources for superconducting accelerators available from industry

Feature	Mode	Gridded tubes	IOT	Klystrons	Magnetron
Operation type		Amplifier	Amplifier	Amplifier	Forced oscillator
Frequency	CW Pulsed	30-470 MHz 30- 470 MHz	0.5-1.3GHz 0.5-1.3GHz	≥350 MHz	~200-2000 MHz
P_{Out}	CW Pulsed	>1000-30 kW >1-0.1 MW	100-30 kW ~100 kW	Up to a few MW	300 kW 600 kW
Gain		14-16 dB	20-23 dB	30 – 50 dB	10-12 dB
Efficiency		Up to 70%	Up to 70%	Up to 65%	More than 90%
HV	CW	Up to 30 kV	Up to 70 kV	≥120 kV	≈ 32 kV
Capital cost of power unit		≈ $6/1 W	≈ $7/1 W	≈ $9/1 W	≈ $1/1 W
Theory, sumylations		Yes	Yes	Yes	Phenomenological models

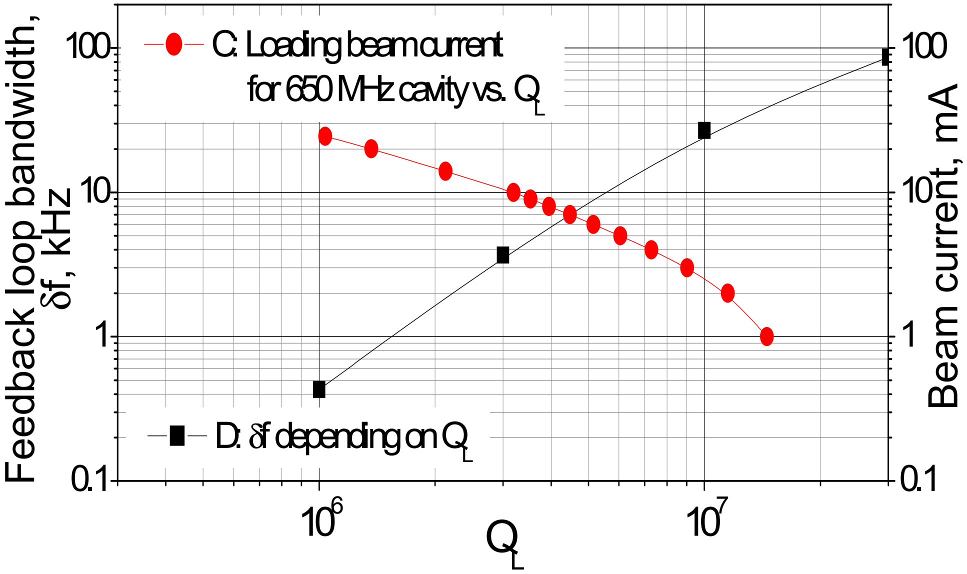
The magnetrons are most efficient RF sources with lowest capital cost!

E. Montesinos, "Gridded tubes", Proton Driver Efficiency Workshop, 29.2-3.2, 2016.
C. Marchand, "Development of efficient Klystrons", Magurele, 3, 23, 2017.
A. Dexter, "Magnetrons for accelerators", Efficient FR Sources Workshop, 6.2014

Required phase and power control for superconducting accelerators

A fast dynamic control of phase and power of the RF sources is required to maintain the phase and amplitude of the accelerating field in the Superconducting RF (SRF) cavities with high accuracy instead of stabilization of the RF sources.

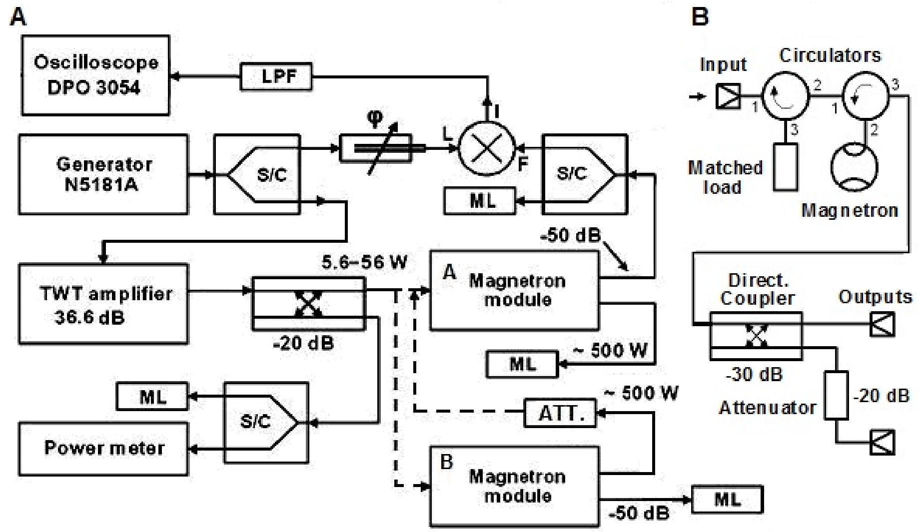
The rate necessary to maintain the admissible instability of the amplitude of the accelerating voltage of ~0.3% in the SRF cavity is determined by Q_L of the cavity and the frequency cut-off of the parasitic modulations, f_m. For 650 MHz SRF cavity with f_m ~65 Hz the plotted diagrams show the required rate of the power control and the accelerated current vs. Q_L.

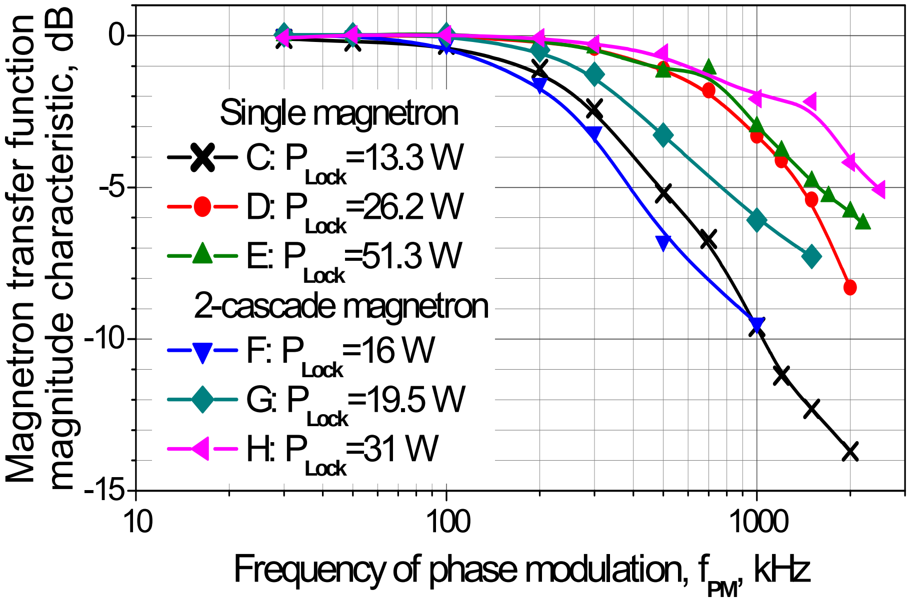


C- the loading beam current for the 650 MHz SRF cavity vs. Q_L D- required bandwidth of the closed feedback loop of power control in SRF cavity vs. its Q_L.

Phase control in magnetrons

The phase control in magnetrons is provided by the phase-modulated resonant ("locking") signal injected into the magnetron.

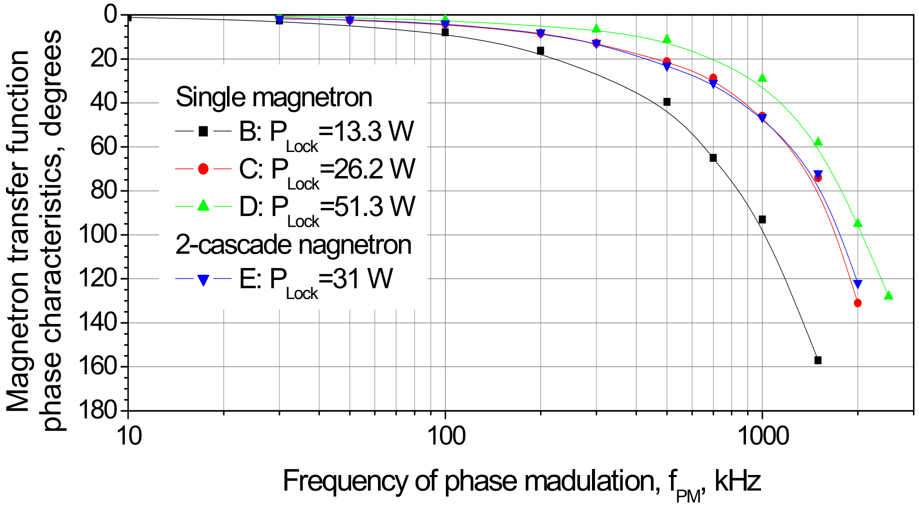




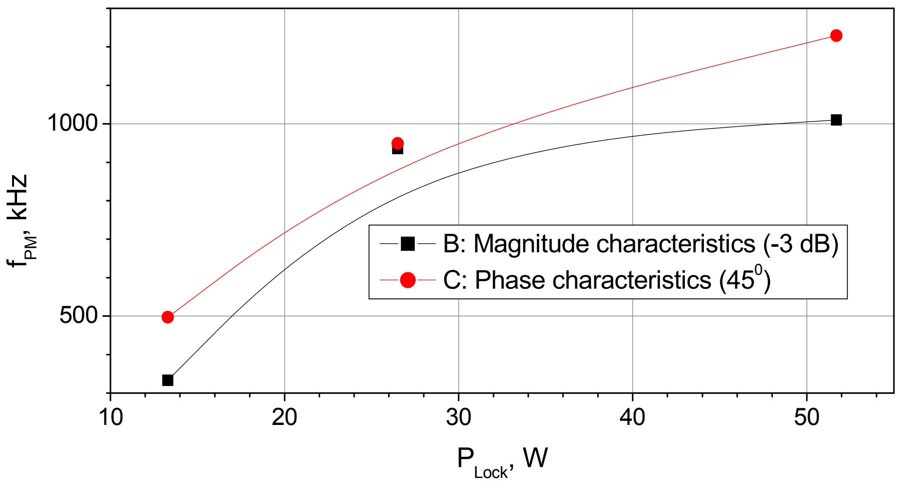
A- schematics for test of single and 2-cascade magnetrons by a phase-modulated frequency-locking signal. S/C is a splitter/combiner, LPF is a low pass filter, ML is a dummy load, and ATT is an attenuator. B- schematics of the magnetron module, [3].

Transfer function magnitude characteristics of the phase control measured in the phase modulation domain at the magnitude of the phase modulation of 4 deg. with 2.45 GHz single and 2-cascade magnetrons in dependence on power of the injection-locking signal, P_{Lock}, [3].

G.Kazakevitch, at al., Muons, Inc., B. Chase, R. Pasquinelli, V. Yakovlev, et al., FNAL, NIM A 760 (2014) 19-27.



Transfer function phase characteristics of the single and 2-cascade 2.45 GHz magnetrons injection-locked by the phase-modulated signal with magnitude of 20 deg. vs. the modulating frequency, f_{PM}, [4].



Estimates of the feedback loop bandwidth at the phase control in 2.45 GHz magnetrons.

The magnitude and phase Bode plots demonstrate capabilities of the magnetrons for a fast dynamic phase control.
In 2014, 2015 were developed and demonstrated vector methods of power control in magnetrons which are reduced to the phase control.

G. Kazakevich, et al., Muons, Inc., V. Lebedev, et al., FNAL, in Proceed. of IPAC17, 4386-4388, 2017.

Vector power control in magnetrons by power combining

The power control is reduced to independent phase control in the both channels of the transmitter with vector summation of the output signals in a combiner.

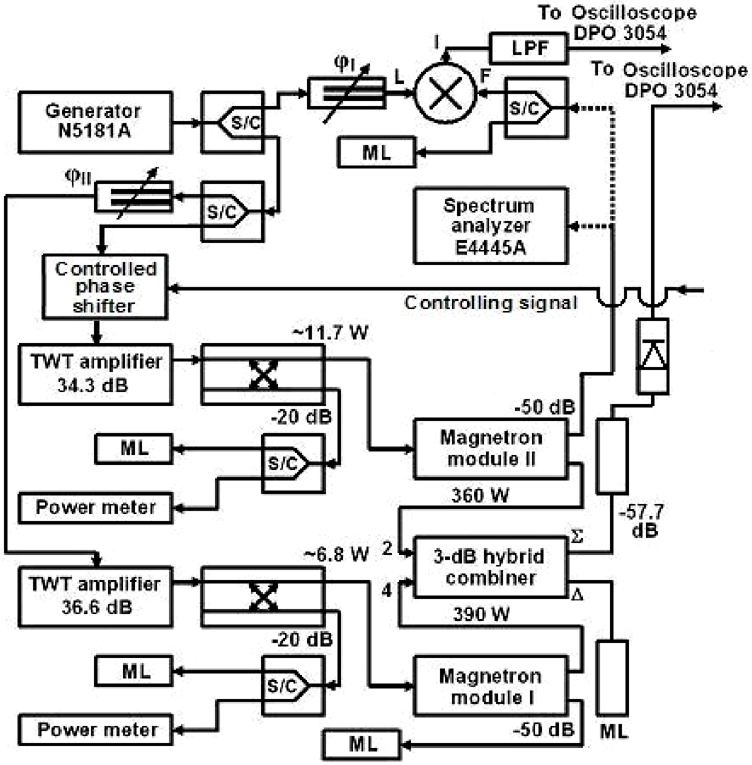


Fig. 10. Setup with the injection-locked magnetrons for test of the power control by power combining.

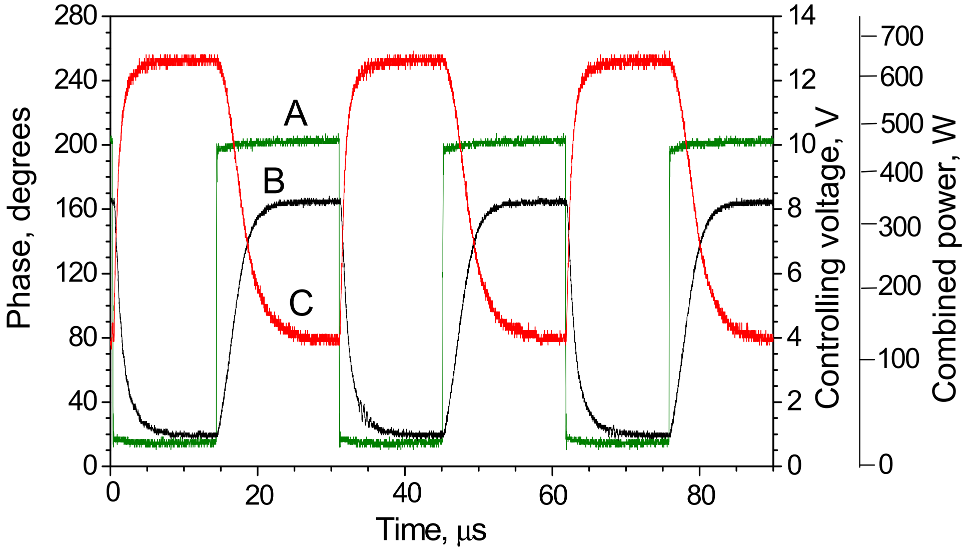


Fig. 13. Power control of the injection-locked magnetrons with power combining. Trace A shows shape of signals controlling the phase shifter, first right scale. Trace B is the phase variations at the output of the magnetron II measured by the phase detector, left scale. Trace C shows power measured at port "S" of the hybrid combiner at the phase shifter control, second right scale.

G.Kazakevitch, at al., Muons, Inc., B. Chase, R. Pasquinelli, V. Yakovlev, et al., FNAL, NIM A 760 (2014) 19-27.

Vector power control in magnetrons by modulation of the depth of phase modulation

A fast modulation of the depth of the phase modulation results in Bessel sidebands. Thus the RF power at the carrier frequency is reduced by the power concentrated in the sidebands.

If the frequency of the depth modulation is much larger than the accelerating frequency bandwidth, the sidebands are reflected from the SRF cavity and absorbed in the dummy load.

The method was verified in experiments with 2.45 GHz SRF cavity driven by a commercial controlled magnetron. At 4 K was achieved the rms of the phase and amplitude deviations of 0.26 deg. and 0.3%, respectively, at the bandwidth of control ~100 kHz.

For now there are the best results obtained with a SRF cavity!

B. Chase, R. Pasquinelli et al.,FNAL, JINST, 10, P03007, 2015.

Pro and Contra of the Vector power control in magnetrons.

The vector methods provide a fast (with the bandwidth of hundreds of kHz) power control in magnetrons utilizing phase-modulated injected resonant signals. They are based on a fast redistribution of the magnetron power between the SRF cavity and the dummy load. This decreases the average efficiency of the RF system up to almost 2 times at a wide range of power control.

Recently we proposed and studied a novel method of power control in which the redistribution of power between the SRF cavity and dummy load is absent. This increases average efficiency of magnetron transmitters at a wide range power control.

The method is based on a wide-range (over 10 dB) power (current) control in a magnetron when the tube is driven by the sufficient (up to -10 dB) resonant injected signal stably operates below and above the threshold of self-excitation. The bandwidth of the control is determined by a bandwidth of the current feedback loop in the magnetron HV power supply. For now it is about of 10 kHz or more without of compromising of the power supply efficiency.

G. Kazakevich, R.P. Johnson, Muons, Inc., V. Lebedev, V. Yakovlev, FNAL, Nim A 839 (2016) 43-51.

Simple analytical model based on of the charge drift approximation for magnetrons driven by a resonant signal

- We discuss a N-cavities conventional CW magnetron with a constant uniform magnetic field H, operating at the frequency ω in the mode with the RF electric field shifted by π in the neighbouring cavity gaps.
- A slow RF wave type $\exp(-i(n\varphi+\omega t))$ is excited at the frequency ω in the interaction space. It rotates with the angular azimuthal velocity $\Omega=2\cdot\omega/N=\omega/n$ in the magnetron slowing system.
- We neglect the impact of space charge and the azimuthal non-uniformity of the static electric field.
- We assume that the magnetron operates being loaded by a matched load with a negligible reflected signal.
- In conventional magnetrons the Larmor radius, $r_L \ll 2\pi c/n\Omega$, where the right part is the length of the synchronous wave in the magnetron slowing RF system. This substantiates consideration of interaction of the Larmor electrons as interaction of charges in centers of Larmor orbits with the synchronous wave.

G. Kazakevich, T. Johnson, Muons, Inc., V. Lebedev, V. Yakovlev, FNAL, “Phase and Power Control in the RF Magnetron Power Stations of Superconducting Accelerators”, arXive_1709.04526.

Drift of the Larmor orbit centers with azimuthal angular velocity Ω in the uniform magnetic field is determined by superposition of the static electric field with the electric potential Φ^0 and the RF field of the synchronous wave.

$$\begin{cases} \dot{r} = -\dfrac{c}{Hr}\dfrac{\partial}{\partial\varphi}\left(\Phi^0 + \Phi\right) \\ \dot{\varphi} = \dfrac{c}{Hr}\dfrac{\partial}{\partial r}\left(\Phi^0 + \Phi\right) \end{cases}$$

For the static electric field: $\Phi^0 = U\ln(r/r_1)/\ln(r_2/r_1)$
E_r = gradΦ^0, $\partial\Phi^0/\partial\varphi = 0$, therefore, $E_\varphi(r)$=0. Here U is the magnetron voltage, and r_1 and r_2 are the magnetron cathode and anode radii, respectively.
The RF field is represented by a scalar potential Φ depended on the ratio, ε, of the radial RF field $\tilde{E}_k$ to the static electric field at the cathode:

$$\Phi = \sum_{k=-\infty}^{\infty}\frac{\tilde{E}_k \cdot r_1}{2k}\left[\left(\frac{r}{r_1}\right)^k - \left(\frac{r_1}{r}\right)^k\right]\sin(k\varphi + \omega t).$$

Here we consider the resonant harmonic $k=n$.

Finally one can get the eqs. for motion of the drifting charges in the frame of the synchronous wave:

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

Here: $r_S = \sqrt{-ncU/(\omega H\ln(r_2/r_1))}$,

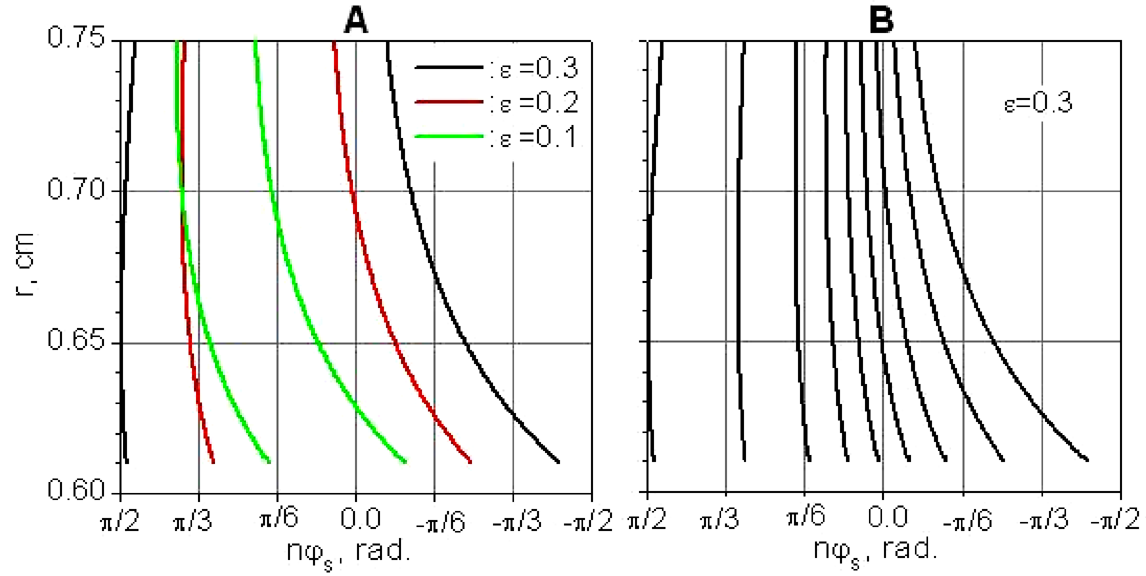
$\varepsilon = \tilde{E}_n/E_1 = \tilde{E}_n \cdot r_1\ln(r_2/r_1)/U$, E_1 is the static electric field at $r = r_1$, and

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

P.L. Kapitza, HIGH POWER ELECTRONICS, Sov. Phys. Uspekhi, V 5, # 5, 777-826, 1963.
L.A. Vanstein and V.A. Soltsev, in "Lectures on microwave electronics", Moscow, Sov. Radio, 1973.

1. The drift of charge towards the anode is possible at $-\pi/2 < n\varphi_S < \pi/2$ with a period of 2π, *i.e.*, only in "spokes".
2. The condition $\varepsilon \geq 1$ does not allow operation of the magnetron. At $\varepsilon=0$, $\dot{r}=0$ and the magnetron can not work.
3. The second term in parentheses of the second equation describes grouping of the charges in a "spoke".

For a typical magnetron with $N=8$, $r_1=5$mm, $r_2/r_1=1.5$, $r_S/r_1=1.2$, at $r \geq r_1+r_L$ at the time interval of the drift from 2 to 10 cyclotron periods, for various magnitudes of the RF field in the synchronous wave were computed trajectories of the drifting charges in a "spoke".



Phase grouping of the charge drifting towards the magnetron anode and contributing to the coherent generation in the considered magnetron model.

G. Kazakevich, T. Johnson, Muons, Inc., V. Lebedev, V. Yakovlev, FNAL, "Phase and Power Control in the RF Magnetron Power Stations of Superconducting Accelerators", arXive_1709.04526.

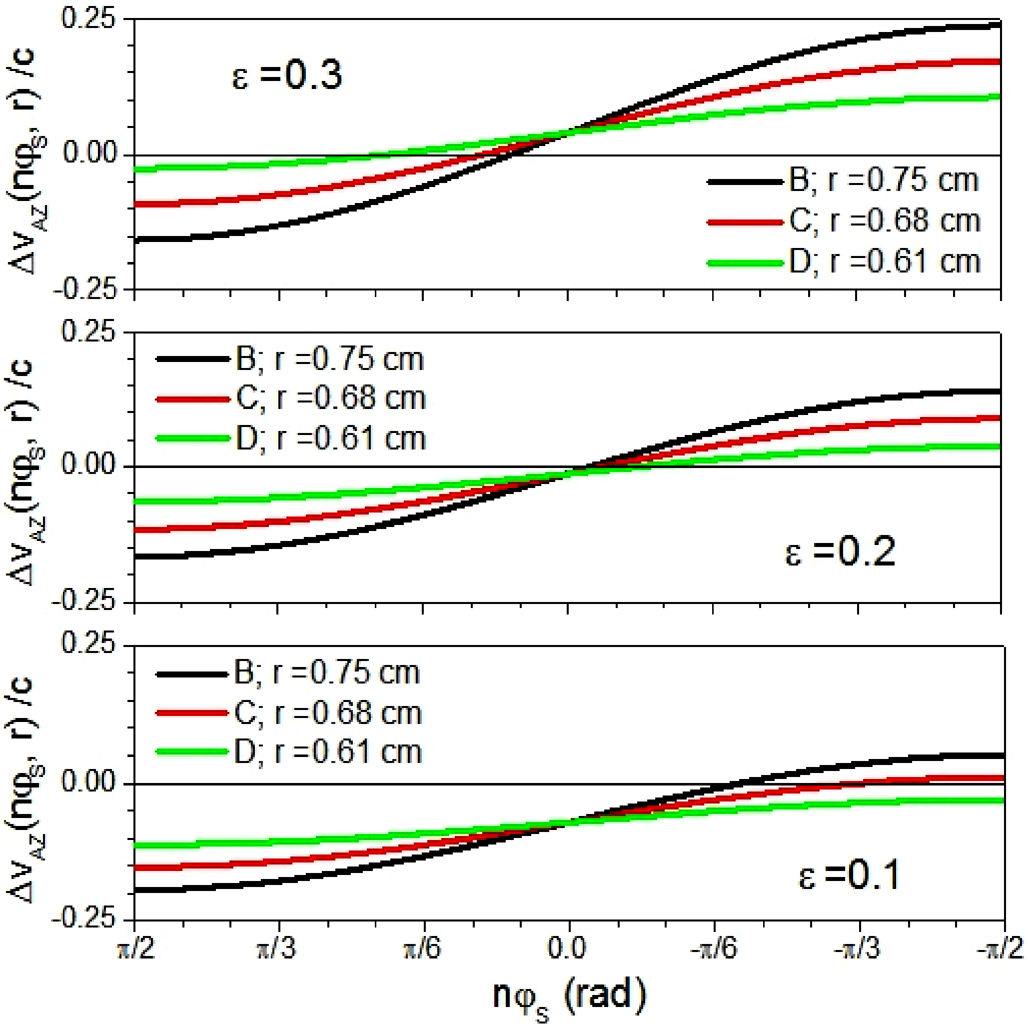
Principle of operation of magnetrons based on a model of the charge drift approximation

- In the frame of the 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 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 greater than the azimuthal velocity of the synchronous wave, the charge being decelerated induces oscillation of the resonant mode in the magnetron RF system and contributes it to the synchronous wave.
- Otherwise, the electric field of the wave accelerates the charge increasing its azimuthal drift velocity. This reduces the wave energy and the wave amplitude.
- Thus, 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 charges and the synchronous wave, $\Delta v_{AZ}(n\varphi_S, r)$.
- The necessary and sufficient conditions for stable generation of magnetrons driven by a resonant injected signal one estimates by requiring a positive values of the integrals of $\Delta v_{AZ}(n\varphi_S, r)$ over the entire phase interval admissible for the "spoke" along the charges trajectories.

D. H. Whittum, "Frontiers of Accelerator Technology", U.S.-CERN-Japan International School, Japan, edited by S. I. Kurokawa, M. Month, and S. Turner (World Scientific, Singapore, London, 1996), pp. 1–135.

The ratio ε of the synchronous wave radial field to the static electric field on the magnetron cathode about of ≈0.3 provides stable generation of the tube even below the self-excitation threshold.

An increase of the synchronous wave energy increases the separatrix size. In this case the charges in a “spoke” may reach the anode as at the beam instability when the charges pump the energy received from the static electric field into the synchronous wave. This provides the stable generation of the tube. Otherwise, a decrease of the synchronous wave energy returns the charges in a “spoke” to stable orbital trajectories without coherent generation.



The difference of the azimuthal velocities of the drifting charges and the synchronous wave in units of *c* at various ε and nφ_S.

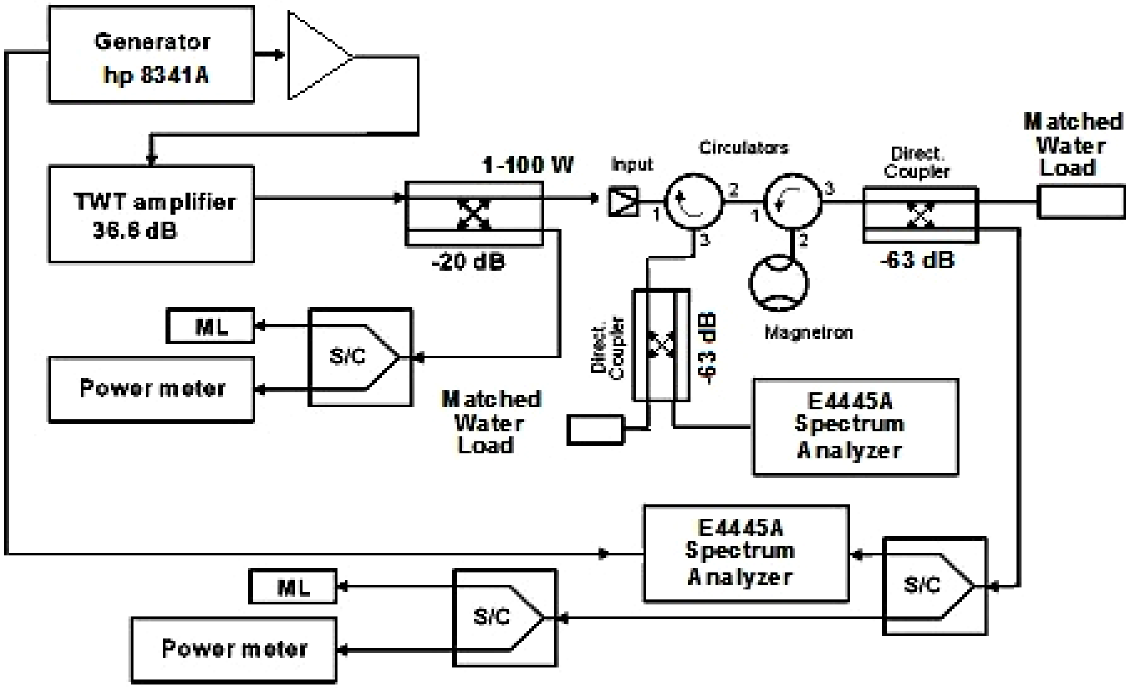
Thus, the strength of the synchronous wave radial electric field determines the necessary and sufficient conditions of stable generation of magnetrons as it follows from the developed analytical model.

From the model follows:

- The magnetron driven a sufficient resonant signal stably operates at the voltage somewhat below the self-excitation threshold providing an extended range of current (power) control.
- The sufficient resonant signal driving the magnetron decreases relative fluctuation of the synchronous wave magnitude. This results in more stable generation of the tube and decreases the phase noise level of the tube.
- The sufficient resonant signal driving the magnetron reduces flux of the drifting charges from a "spoke". This flux worsens the phase grouping and increases the decrement of the RF energy from the synchronous wave notably decreasing the magnetron efficiency at low power.
- A notable decrease of the injected resonant signal when the magnetron operates below the self-excitation threshold leads to damping of the synchronous wave. This stops generation of the magnetron.

All this was verified in the following experiments with 2.45 GHz magnetrons.

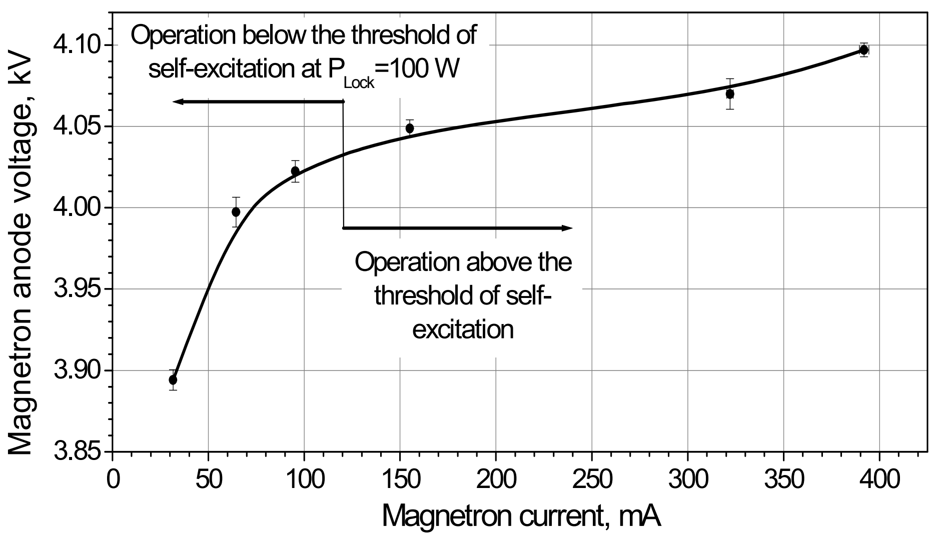
Experimental verification of the proposed magnetron model

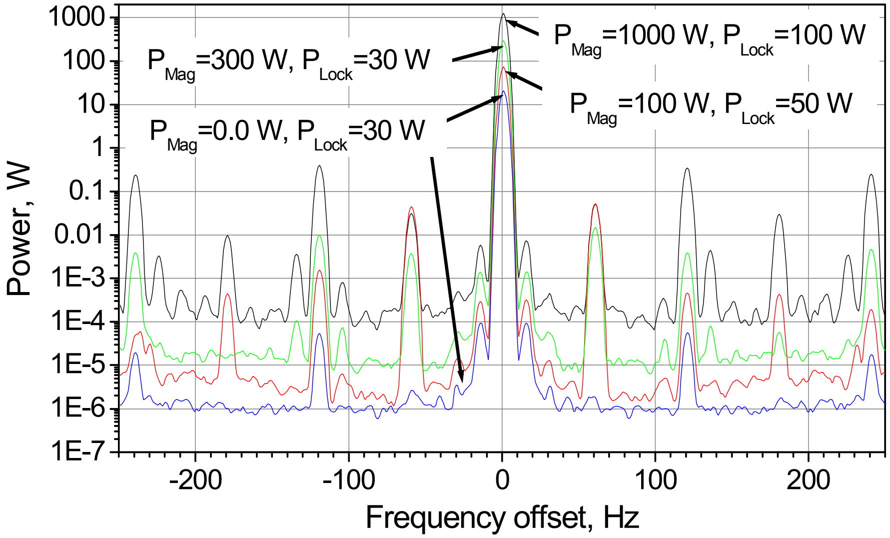


The magnetron setup to test the magnetron frequency stability, noise, and efficiency in CW regime.

G. Kazakevich, Muons, Inc., V. Lebedev, V. Yakovlev, FNAL, NIM A 839 (2016) 43-51.

Stability of magnetron operation below and above the self-excitation threshold





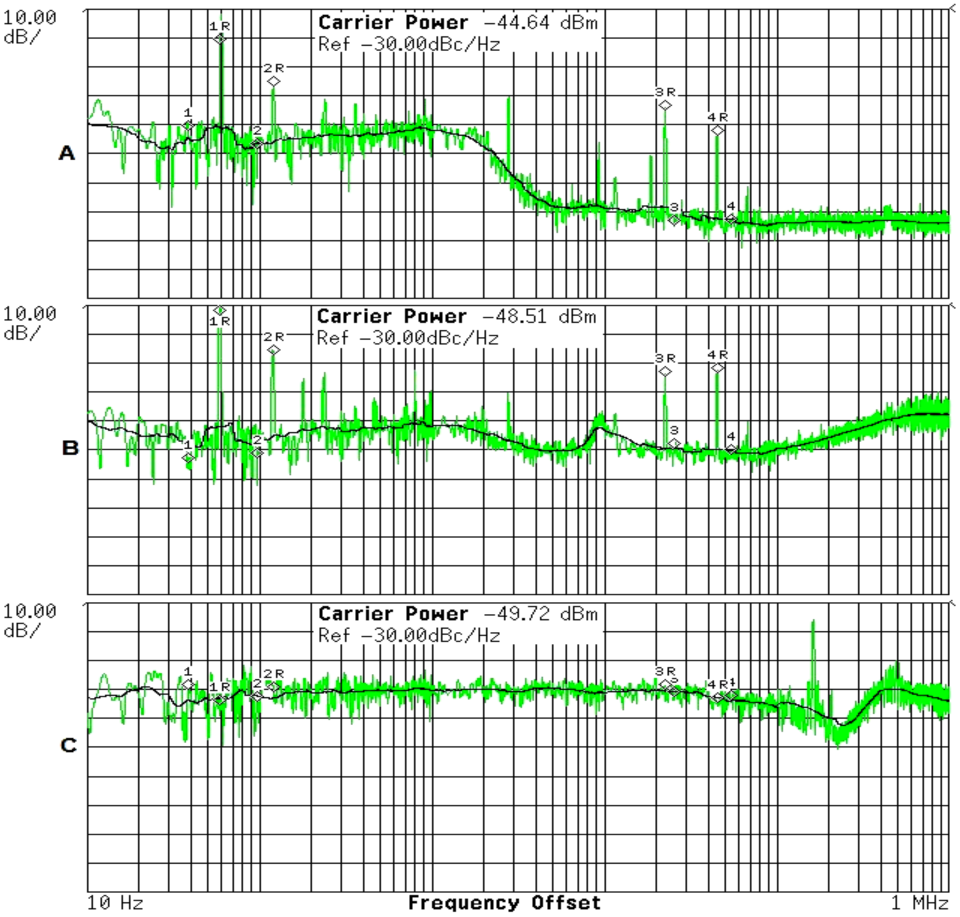
V-I characteristic of 1.2 kW measured at P_{Lock} =100 W. The solid line (B-spline fit) shows available range of current with stable operation of the 2.45 GHz CW tube at the given P_{Lock}.

Offset of the carrier frequency at various powers of the magnetron, P_{Mag}, and the injected signal P_{Lock}. The traces at P_{Mag} =100 and 300 W were measured below the self-excitation threshold. The trace P_{Mag} =0.0 W, P_{Lock} =30 W shows the frequency offset of the injected signal when the magnetron HV is OFF.

G. Kazakevich, et al., Muons, Inc., V. Lebedev, et al., FNAL, in Proceed. of IPAC17, 4386-4388, 2017.
G. Kazakevich, Muons, Inc., V. Lebedev, V. Yakovlev, FNAL, NIM A 839 (2016) 43-51.

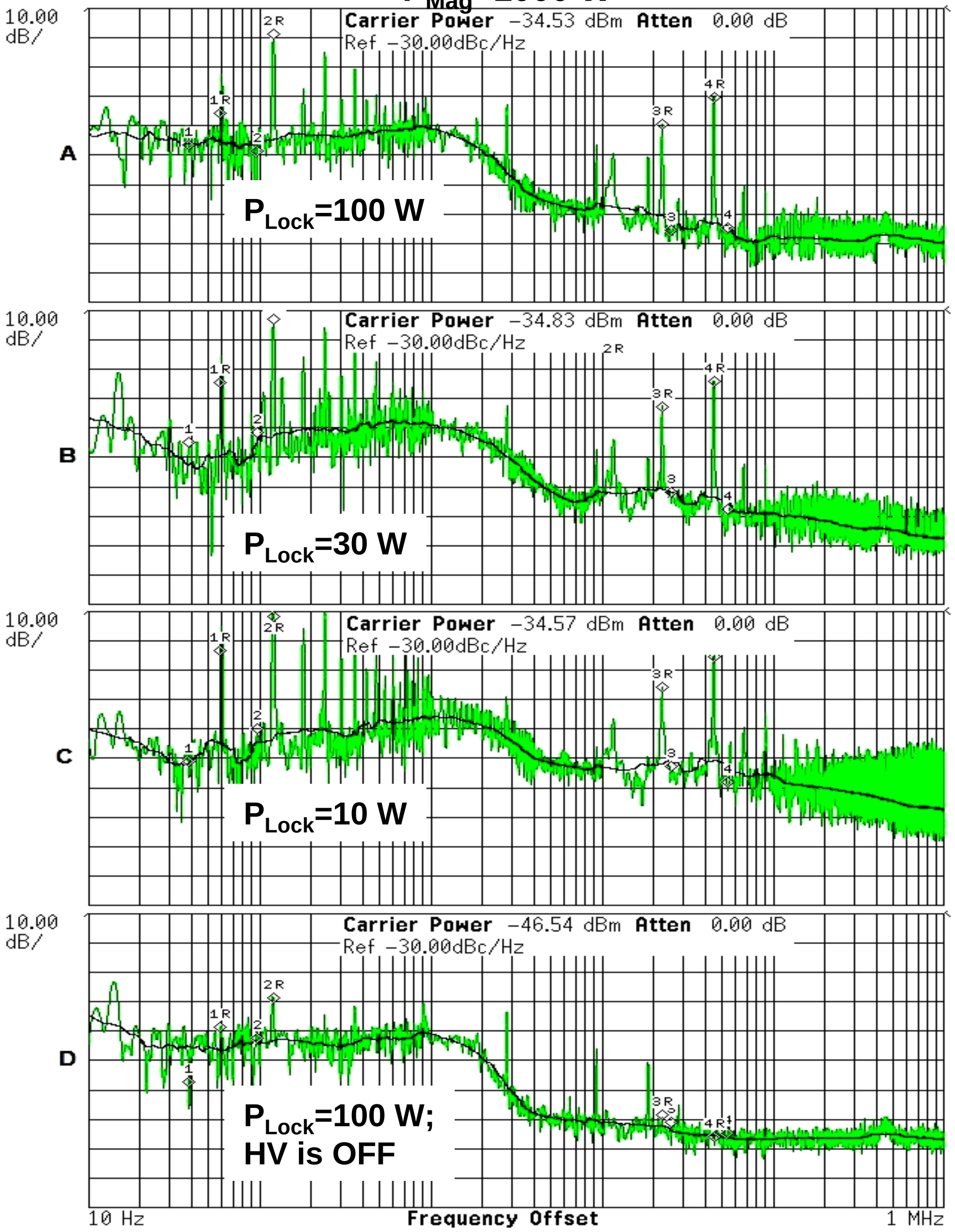
The spectral power density of the noise

P_{Mag}=100 W

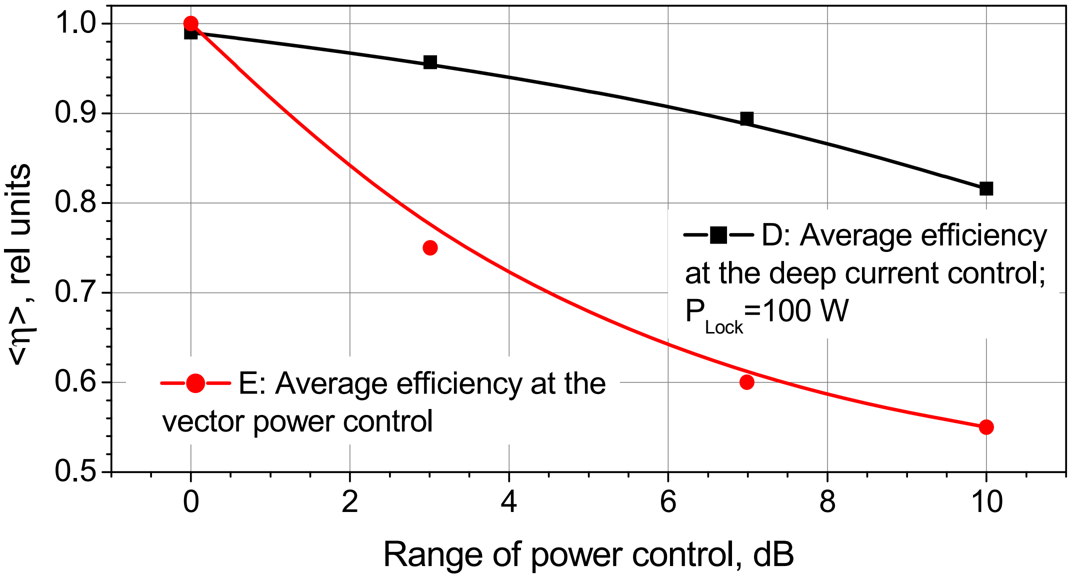


The spectral power density of the noise at various power levels of the locking signal at P_{Mag} = 100 W. A - P_{Lock} =100 W, B - P_{Lock} =30 W, C - P_{Lock} =10 W, Black traces show the averaged spectral density of the noise.

P_{Mag}=1000 W

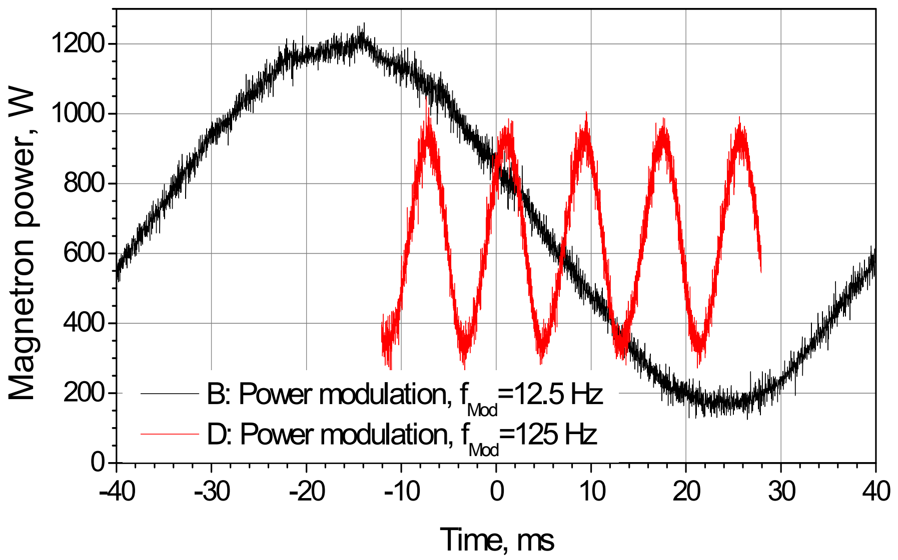


Average efficiency of magnetrons operating at a wide range of power control



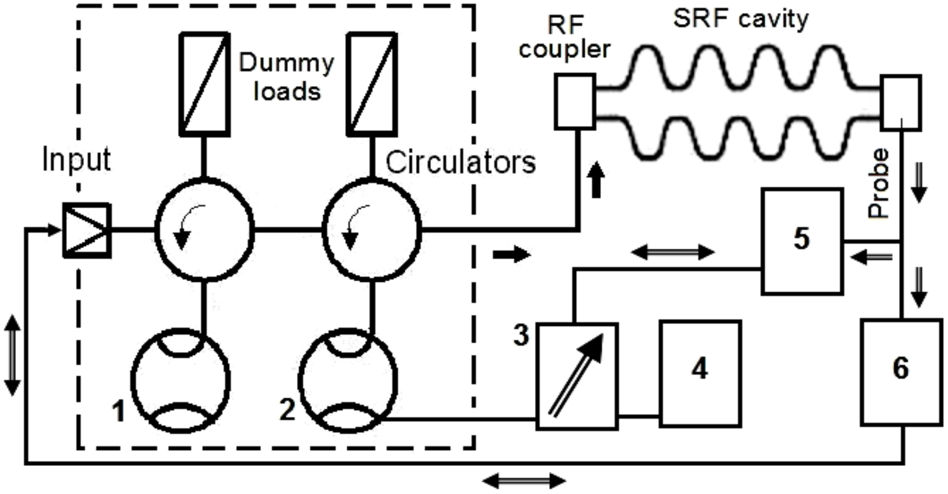
Relative averaged magnetron efficiency vs. range of power control for various methods of control. D- is average efficiency of the 1.2 kW magnetron driven by the injected resonant signal of -10 dB and measured at deep magnetron current control. E- is average efficiency of 1 kW magnetrons with vector power control.

Dynamic wide-range power control in magnetron



Modelling of a dynamic power control by a wide-range management of magnetron current with a harmonic signal controlling the HV switching power supply with a current feedback loop.

Highly-efficient magnetron transmitter concept



1- the low power magnetron, 2- the high-power magnetron, 3- the low-power HV power supply controlled within the feedback loop, 4- the main uncontrolled HV power supply, 5- the current/voltage controller within the LLRF system for the low-power supply, 6- the phase controller within the LLRF system.

G. Kazakevich, et al., Muons, Inc., V. Lebedev, et al., FNAL, in Proceed. of IPAC17, 4386-4388, 2017.

Summary

- ***The presented analytical model considering the resonant interaction of the synchronous wave with the drifting charges grouped in phase as the basis of operation of magnetrons allows optimizing the injected resonant signal for operation of the tube with high stability, high efficiency and low noise in accordance with requirements of high-current superconducting accelerators. The performed experiments demonstrated that behaviour of magnetrons driven by the resonant injected signal and fed below and above the self-excitation threshold is well explained and substantiated by the described analytical model.***

- ***The model demonstrating a fine physics in operation of magnetrons substantiates the novel method of power control in magnetrons over 10 dB range providing high stability, efficiency and low noise. The proof of the principle of the method was verified in experiments.***

- ***A novel method of power control in magnetrons can be combined with vector methods. This will allow a wide-band phase and power control at highest efficiency of the magnetron transmitters. This is important for modern superconducting accelerators with megawatts beams.***

Great gratitude to Muions, Inc. President Dr. R. Johnson and the Authorities of the Fermilab Technical and Accelerator Divisions restored scientific cooperation Muons, Inc and Fermilab in the study of magnetrons!

Lot of thanks to John Reid for equipping of our facility by the necessary techniques!

Lot of thanks to my colleagues Timergali Khabibouline and Gennady Romanov from Fermilab TD for their help in assembly of the facilities and start of experiments in TD1!

Thank you!