A Novel Technique of Power Control in Magnetron Transmitters for Intense Accelerators

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Requirements to modern accelerators

Projects of large-scale, intensity-frontier accelerators assume CW beams at a megawatt power and energy in a GeV range. Requirements of economics dictate minimization of the capital cost, (~ $ 1 B or more for modern large projects) and the cost of operation of the facilities.

► The capital cost of the RF system is a significant part of the project capital cost. It is determined by total required power of the RF system and the cost of power unit.

► The cost of operation is determined by efficiency of acceleration and efficiency of the RF sources.

► Minimization of the operating cost leads to utilization of the Superconducting RF (SRF) cavities and powering of the cavities by most efficient RF sources with less expensive cost of power unit.

► Utilization of superconducting RF (SRF) cavities provides highest efficiency of acceleration, but requires a compensation of parasitic phase and amplitude modulations inherent in operation of the SRF cavities. The modulations resulted from cavity detuning by mechanical vibrations of the cavity walls can be compensated by the dynamic control of the phase and power of the RF sources at the bandwidth of the control in a few kHz or wider.

► The parasitic modulations are not associated with instability of the RF sources.

► The traditional RF sources (klystrons, IOTs, Solid-State (S-S) amplifiers) used presently for powering of SRF cavities provide RF power with cost of about of $5, $10 and $ 15 per Watt, respectively.

► RF power of L-band commercial high-power CW magnetron transmitters costs ~$1 per W. Their efficiency is higher than that for any traditional RF source.

Estimates for 1 GeV, 2.5 MW beam acceleration with various RF sources:
Power with acceleration gain of 20 MV/cavity is 50 kW/cavity. Compensation of the parasitic modulation requires ~50 kW, i.e., one needs up to ~100 kW/cavity. For 1 GeV beam total RF power is 5 MW. The capital cost of the RF system with klystrons is $25 M, with S-S amplifiers is $75 M, with magnetrons is $5 M.

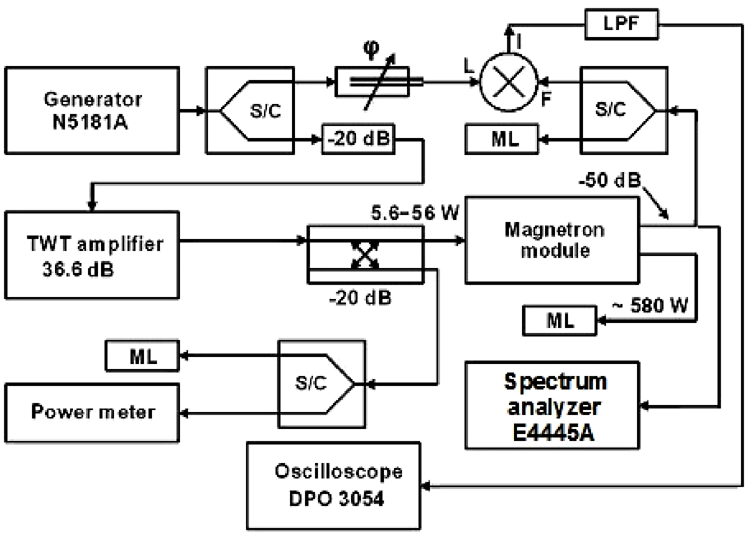
► Utilization of magnetrons will save tens of millions of dollars in capital cost.

► The magnetrons driven by a resonant (injection-locking) signal with a sufficient power provide phase control at the bandwidth in MHz range[1]. Power combining with a 3-dB hybrid allows a dynamic power control by a magnetron 2-channel transmitter with the same bandwidth[Ibid] at any load impedance.
Power control by an additional modulation of the phase modulation depth allowed reaching rms phase and amplitude deviations of the RF field in a 2.45 GHz SRF cavity of 0.26 deg. and 0.3% respectively[2] at the cavity loaded Q-factor of 10^7.

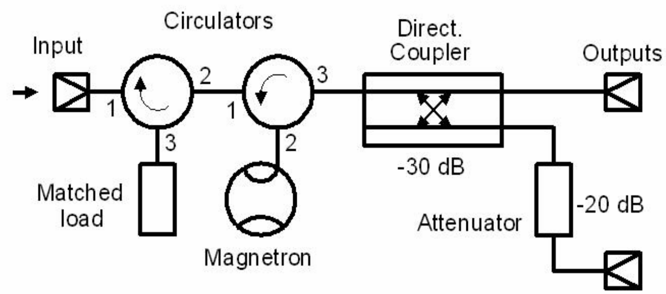
A Novel Technique of Power Control in Magnetrons

► The technique was substantiated by a developed kinetic model considering drift of the charge in space of interaction of magnetrons in presence of synchronous wave. The wave establishes necessary and sufficient conditions for coherent oscillation in magnetrons.

► Analysis of the drift equation and its solution indicate capability of operation of the magnetron excited by a sufficient resonant signal at the voltage less than threshold at self-excitation, i.e., at the magnetron current (power) less than available minimum current in free run[3]. This extends the range of magnetron power control. Estimations of the extended range are in agreement with measured results.



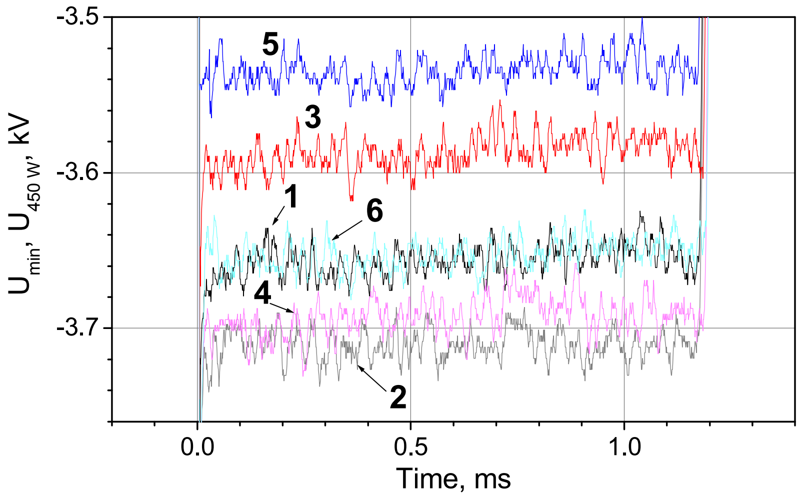
Scheme of the measurements



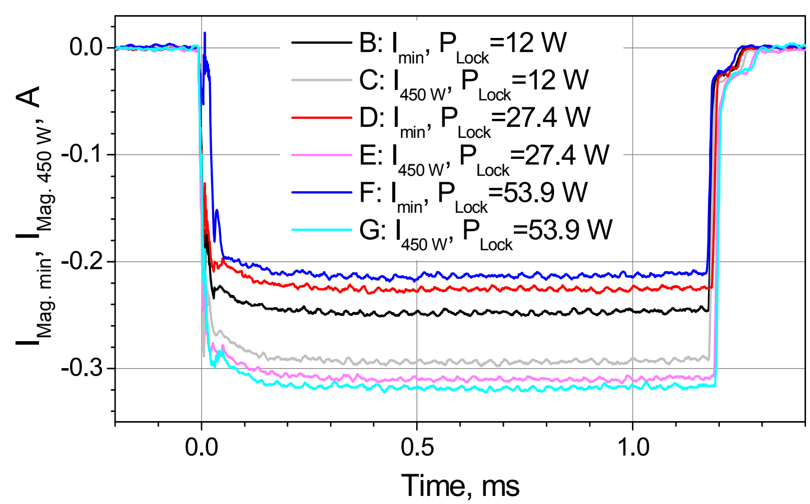
Scheme of the magnetron module

Experimental verification of our concept in pulsed regime

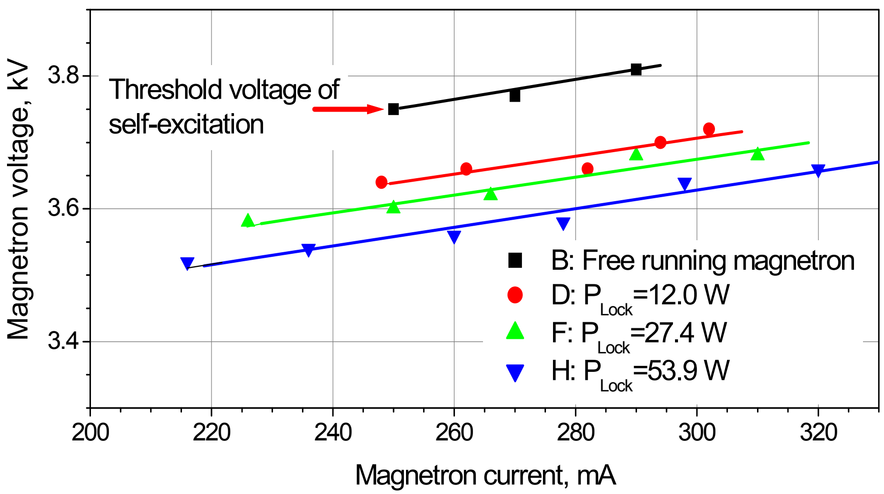
The magnetron pulsed voltage and current were measured by a compensating divider and a transducer, respectively. Inaccuracy of the measurements did not exceed ±1%.



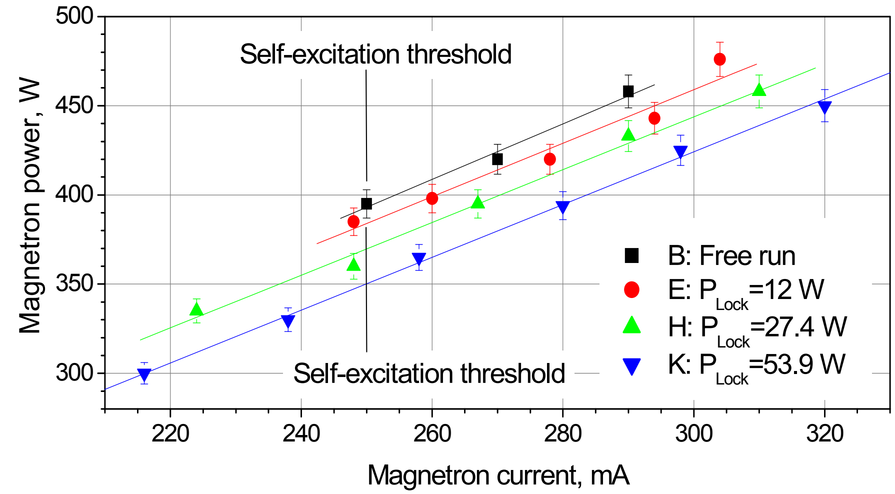
Measured pulsed magnetron voltage at the minimum generated power, traces 1, 3, 5, and at a power of 450 ±8 W, traces 2, 4, 6 at the following powers of the frequency-locking signal, P_{Lock}: 12 W, traces 1 and 2; 27.4 W, traces 3 and 4; 53.9 W, traces 5 and 6, respectively.



Traces of the measured magnetron pulsed cathode current at minimum generated power and at a power of 450 ±8 W at various powers of the frequency-locking signal, P_{Lock}.



Measured at a constant magnetic field the V-I characteristics of the free running, dots B, or pre-excited injection-locked magnetron, dots D, F, H at various P_{Lock}.



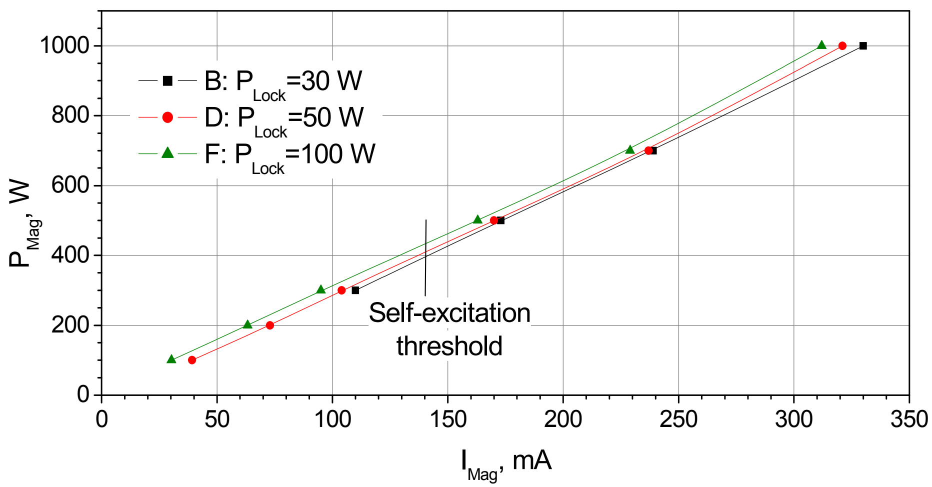
Dots with error bars: dependence of the magnetron pulsed power on the magnetron current for free running and pre-excited tube at various power of the pre-exciting signal.

► Since the dynamic impedance of magnetrons, Z_D is about of 10% of the static impedance, Z_S, one can write: $\Delta P/P \sim (\Delta U/U) \cdot Z_S/Z_D$, i.e., a wide variation of magnetron power requires a narrow variation of the magnetron voltage.

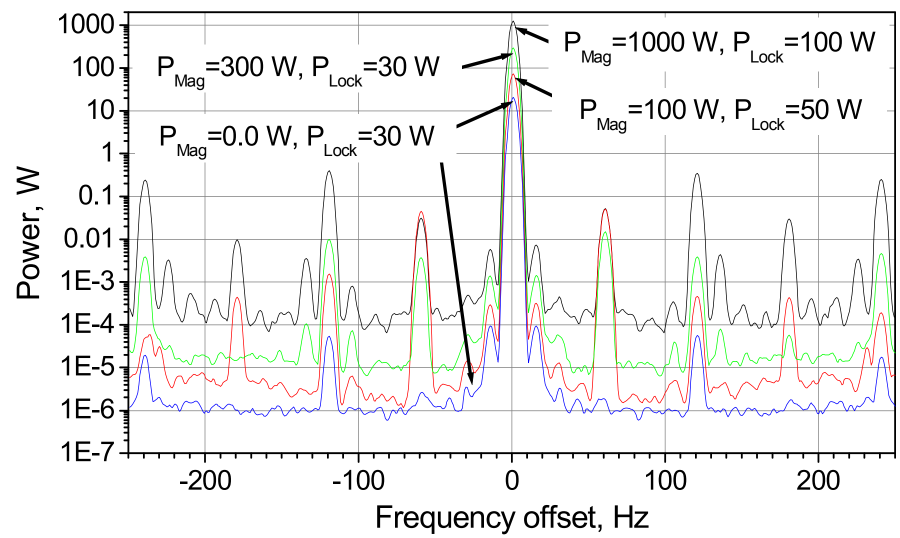
► The experiments clearly verified our concept of the extended current (power) control at a sufficient resonant driving signal and the model we have developed as well.

Experimental verification of our concept in CW regime

More detailed measurements of power variation at various values of the locking power were performed in CW mode with 2.45 GHz, 1.2 kW magnetron type YJ1540 with a permanent magnet. The magnetron was fed by a switching power supply operating as a current source.



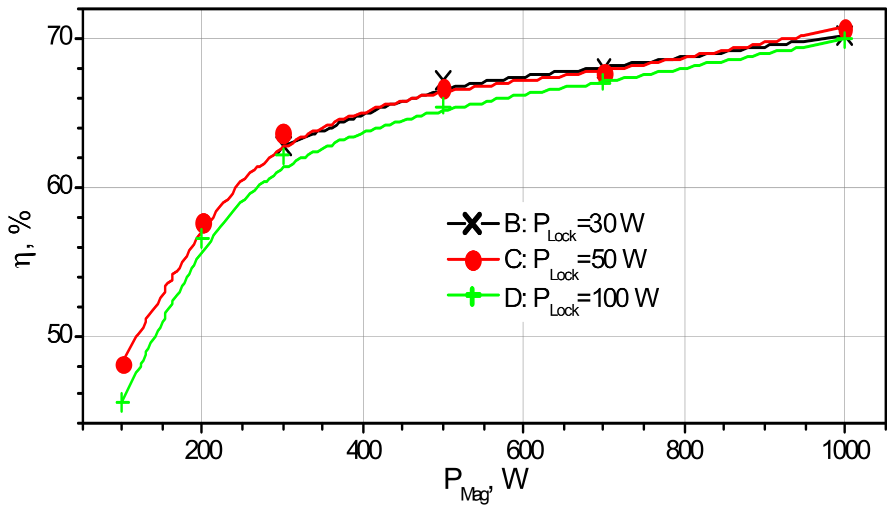
Measured dependence of power of the injection-locked magnetron on the magnetron current in CW mode.



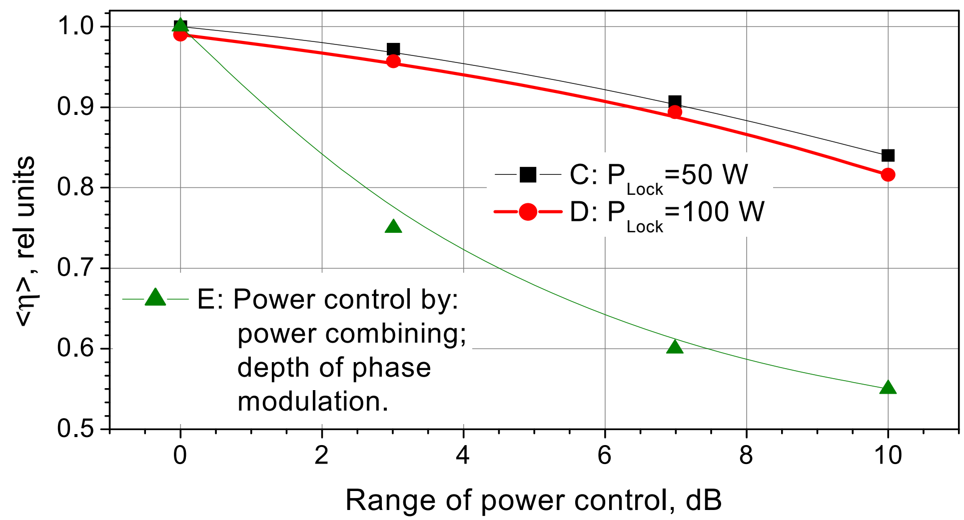
Offset of the magnetron carrier frequency at various power levels of the magnetron, P_{Mag}, and the locking signal, P_{Lock}.

► Measured offsets of the carrier frequency at various levels of power of the magnetron and the locking signal demonstrate precise stability of the magnetron carrier frequency at the proposed magnetron control.

Efficiency of CW magnetrons at a wide range power control



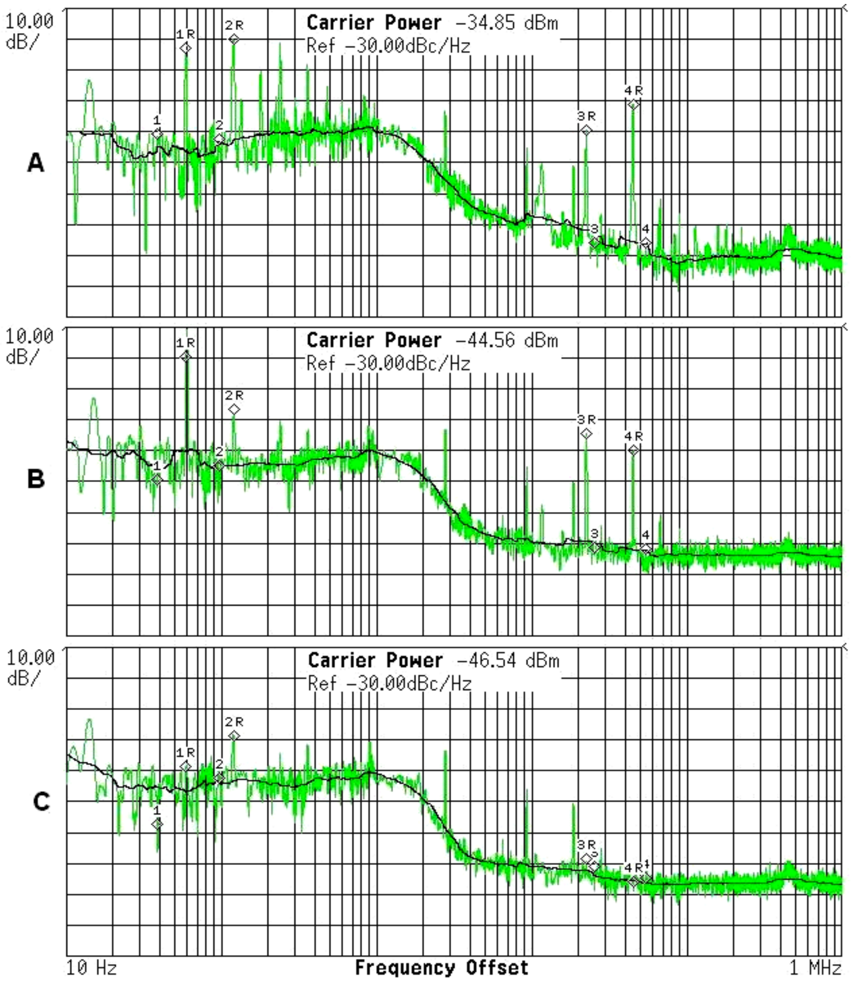
Absolute efficiency of the pre-excited injection-locked 1.2 kW magnetron with power control by management of the magnetron current in a wide range.



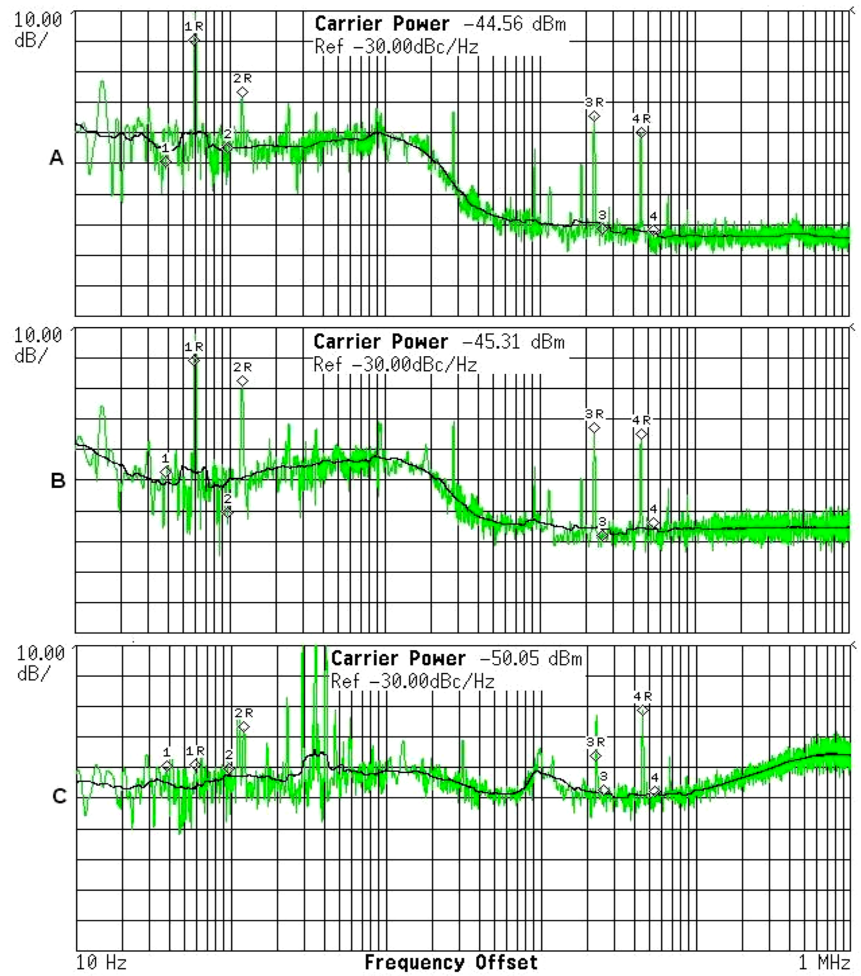
Relative efficiency at various methods of power control

► The experiments clearly demonstrated highest efficiency obtained with the proposed method of the extended current (power) control in magnetrons.

Spectral density of magnetron signals at a wide range of power control vs. power of the driving resonant signal



P_{Lock}=100 W; A- P_{Mag}=1000 W, B- P_{Mag}=100 W, C- trace of the locking signal

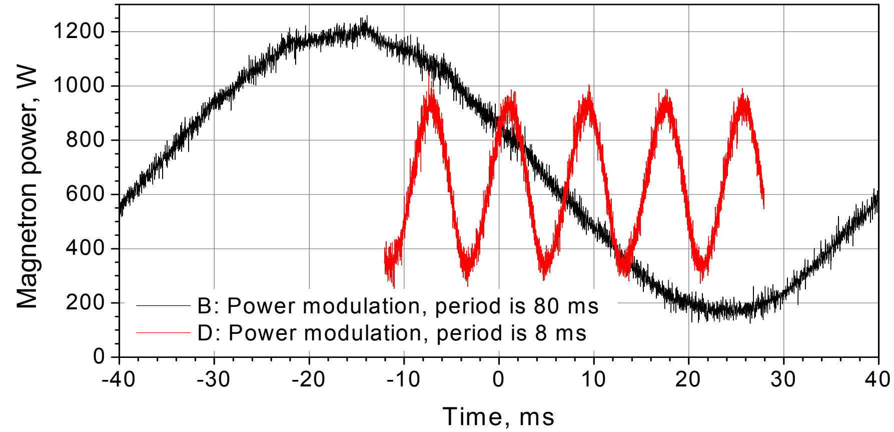


P_{Mag}=100 W; A- P_{Lock}=100 W, B- P_{Lock}=50 W, C- P_{Lock}=30 W

Modeling of dynamic power control in magnetrons by a control of current in an extended range

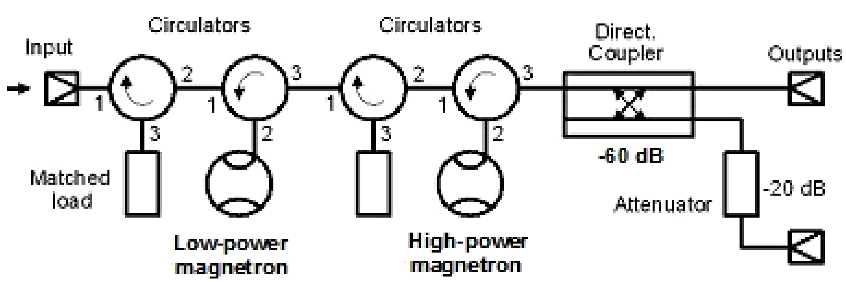
► Modeling of a dynamic control of magnetron was performed by modulation of current of the magnetron HV power supply.

The magnetron power was calibrated vs. the magnetron current with accuracy better than ±1%.



Modulation of the magnetron power by control of current in an extended range at P_{Lock}=100 W.

Highly-efficient magnetron transmitter concept



Conceptual scheme of the 2-cascade transmitter

The low-power magnetron provides a wideband phase control of the signal, frequency-locking the high-power magnetron. The power control is realized by modulation of current in the high-power magnetron which can operate at the voltage less than the voltage of self-excitation.

Summary

- A kinetic model of phase focusing in magnetrons by a synchronous wave was developed and experimentally studied. The model substantiates stable operation of the magnetron fed by the voltage less than the threshold of self-excitation (the Hartree voltage) at a sufficient resonant driving RF signal. This allows extending the range of magnetron power control at highest efficiency.
- Proof of principle of the extended range of the power control (up to 10 dB) of the magnetron driven by a sufficient resonant (injection-locking) signal was demonstrated with 2.45 GHz, 1 kW, CW magnetrons operating in pulsed and CW regimes below the Hartree voltage.
- The magnetrons driven by the sufficient resonant signal at the extended range of power control provide precisely-stable carrier frequency, low noise, wide bandwidth of phase control and capability of dynamic power control with a suitable bandwidth of the current control in HV sources.
- The developed method of power control in magnetrons allows development of RF sources suitable for superconducting accelerators, providing cost of RF power ~$1-2 per watt at highest efficiency. This will save tens to hundred of millions of dollars in capital and operation costs for the ADS class projects.

References

[1]G. Kazakevich, R. Johnson, G. Flanagan, F. Marhauser, V. Yakovlev, B. Chase, V. Lebedev, S. Nagaitsev, R. Pasquinelli, N. Solyak, K. Quinn, D. Wolff, and V. Pavlov, NIM A 760 (2014) 19-27.

[2] B. Chase, R. Pasquinelli, E. Cullerton, Ph. Varghese, JINST, 10, P03007, 2015.

[3] G. Kazakevich, V. Lebedev, V. Yakovlev, V. Pavlov, NIM A 839 (2016) 43-51.

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Thank you!