

# HIGH-POWER MAGNETRON TRANSMITTER FOR THE ELECTRON COLLIDER RING OF THE MEIC FACILITY\*

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## Abstract

Operation of the 3-12 GeV electron collider 8-shape ring of the MEIC facility causes a Synchrotron Radiation (SR) of electrons in arcs with energy loss of ~20 kW/m at beam current of ~3 A. The total SR loss up to 2 MW per a turn is presumed to compensate by Superconducting RF (SRF) accelerating cavities. To minimize the beam emittance, each individual SRF cavity is proposed to feed by an individual and independent CW RF source allowing a wide-band control in phase and power. Most efficient and less expensive in capital and maintenance costs the high-power transmitters based on magnetrons, injection-locked by phase-modulated signals, controlled in wide-band are proposed as the RF sources. The magnetron RF CW sources utilizing 2-cascade magnetrons allowing a wide-band phase and power control by the injection-locking phase-modulated signals were experimentally modelled by 2.45 GHz, CW, 1 kW magnetrons. Results of additional modelling and adequacy of the transmitters for the SRF cavities are discussed in the presented article.

## INTRODUCTION

Compensation of the SR losses in arcs of the electron collider of the MEIC project requires high-power CW RF sources for acceleration of the electrons in SRF cavities keeping the accelerating voltage phase and amplitude deviations in each cavity significantly less than 1 degree and 1% of nominal, respectively. The strict requirements follow from necessity in a precise orientation and positioning of the highly compressed electron bunches relatively the proton/ion bunches. Therefore minimization of emittances of the electron bunches is one of general requirements at compensation of the SR losses. The low-noise RF sources with a precisely-stable carrier frequency allowing a wide-band dynamic phase and power control by a feedback within closed loops, eliminating the parasitic amplitude and phase modulation inherent in the SRF cavities, are necessary to compensate the SR losses.

The traditional CW RF amplifiers (klystrons, IOTs, solid-state amplifiers) are applicable for this task, but they associate with high capital and maintenance costs, [1, 2]. Utilization of high-power klystrons feeding groups of the SRF cavities decreases the costs in some degree, but does not allow minimizing the beam emittances because of non-optimized phase and amplitude of RF field in individual cavities. Capability of transmitters based on 2-

cascade magnetrons, frequency-locked by phase-modulated signals for a dynamic phase and power control of RF field in SRF cavity was shown in [3]. A dynamic control of a CW magnetron, frequency-locked by wide-band phase-modulated signal, stabilizing RF field in the SRF cavity, in phase and power up to 0.26 deg. rms and 0.3% rms, respectively, was first demonstrated in [4].

The results reinforce our proposal on the use of the magnetron transmitters for feeding of the SRF cavities compensating SR losses in the electron ring of MEIC. The transmitter models capabilities and tests are considered in the presented work.

## MAGNETRONS WITH A WIDE-BAND PHASE CONTROL

Operation of the phase-controlled frequency-locked magnetron one can represent considering the transient processes in the magnetron caused by frequency/phase pulling and pushing. Since the magnetron is assumed to be frequency-locked, the magnitude of the locking signal has to be significantly more than the signal reflected from the SRF cavity into magnetron. The standard ferrite circulators have inverse losses  $\geq 20$  dB, so the locking signal power of  $> -15$  dB for the magnetron may be enough to obtain precisely-stable carrier frequency in the SRF cavity at variable beam loading.

As it is shown in [3], the equation, describing phase pulling/ pushing in the frequency-locked magnetron at a steady-state is transformed into the following expression:

$$\tilde{V}_M = \cos \psi \cdot \exp(i\psi) \cdot \left( \frac{2Q_{LM}}{Q_{EM}} \tilde{V}_{FM} - \frac{Q_{LM} \cdot R_{ShM}}{2 \cdot Q_{OM}} \tilde{I}_M \right). \quad (1)$$

Here:  $Q_{OM}$ ,  $Q_{LM}$  and  $Q_{EM}$  are unloaded, loaded and external Q-factors of the magnetron cavity, respectively,  $\tilde{V}_M$ ,  $\tilde{V}_{FM}$  and  $\tilde{I}_M$  are phasors of the voltage in magnetron cavity, of the injection-locking signal, and of the magnetron current, respectively,  $\beta$  is the magnetron cavity coupling coefficient,  $R_{ShM}$  is the magnetron shunt impedance, and  $\psi$  is angle between sum of phasors  $-(2Q_{LM}/Q_{EM}) \cdot \tilde{V}_{FM}$ ,  $(Q_{LM} \cdot R_{ShM}/2 \cdot Q_{OM}) \cdot \tilde{I}_M$  and  $\tilde{V}_M$ , Fig. 1, [5].

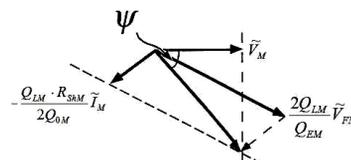


Figure 1: Phasor diagram of the injection-locked magnetron.

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Assuming constant the voltage in the magnetron cavity, at variations of the locking signal and the magnetron current one can write the difference equation for imaginary terms, obtained from the eq. (1), [6]:

$$\delta\psi \cong \frac{\sin 2\psi \left( \frac{2\beta}{\beta+1} \frac{\delta|\tilde{V}_{FM}|}{|\tilde{V}_M|} - \frac{R_{ShM}}{2(\beta+1)} \frac{\delta|\tilde{I}_M|}{|\tilde{V}_M|} \right)}{(6\sin^2 \psi - 2) \cdot \left( \frac{2\beta}{\beta+1} \frac{|\tilde{V}_{FM}|}{|\tilde{V}_M|} - \frac{R_{ShM}}{2(\beta+1)} \frac{|\tilde{I}_M|}{|\tilde{V}_M|} \right) + 1}, \quad (2)$$

The equation shows that variation of the locking signal amplitude and/or phase and variation of the magnetron current rotate phasor of the voltage in the magnetron cavity. It means that varying (controlling) phase of the locking signal one can control phase at the magnetron output, e.g. compensating phase pulling and pushing. It is a basis of the proposed phase control of the magnetron by phase-modulated injection-locking signal, [3].

According to requirements of compensation of the SR losses the average power per a SRF cavity has to be quite high,  $\geq 100$  kW/cavity. To decrease the driving RF power, the 2-cascade frequency-locked magnetrons allowing wide-band phase control, Fig. 2, are proposed.

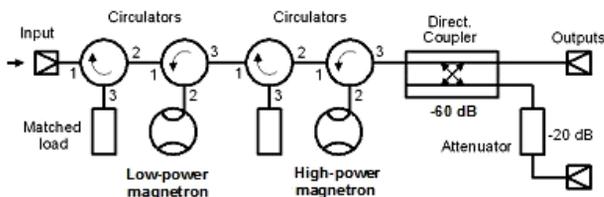


Figure 2: Conceptual scheme of a 2-cascade magnetron with 3-port circulators allowing a wide-band phase control.

In the setup the first, low-power magnetron, injection-locked by an external driver, injection-locks the second, high-power magnetron, [7].

The wide-band phase control of single and 2-cascade magnetrons was verified in experiments with 2.45 GHz, 1 kW, CW magnetrons operating in pulsed mode, [3], at pulse duration of 5 ms. Plots of phase response of the magnetrons vs. frequency of phase modulation,  $f_{PM}$ , at various power of the locking signal are shown in Fig. 3.

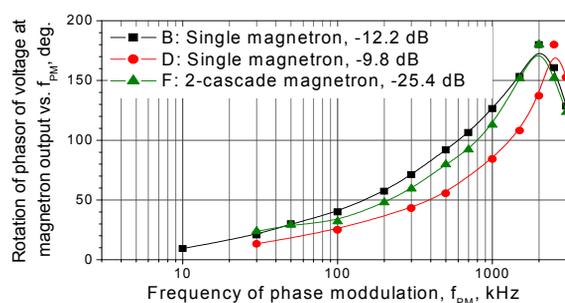


Figure 3: Angle of rotation of the phasor of voltage in the wave at output of the frequency-locked magnetrons vs. the modulating frequency,  $f_{PM}$ , in various setups, at various locking power. Magnitude of 20 deg was used for phase modulation at the measurements.

Figure 4 shows measured transfer function magnitude characteristics of magnetrons frequency-locked by phase-modulated signal. The measurements were performed in pulsed mode, in phase-modulation domain at magnitude of phase modulation of the frequency-locking signal of 4 deg., [3].

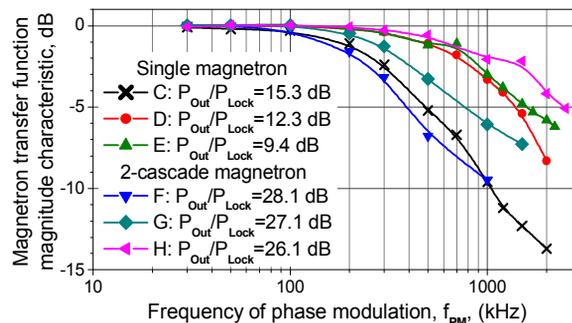


Figure 4: Transfer function magnitude characteristics of the frequency-locked magnetrons measured at various power of the locking signal.

As it follows from Figs 3, 4 the bandwidth of the phase control in 2-cascade magnetron in MHz range is available at power of the injection-locking signal,  $P_{Lock} \geq -12$  dB/tube. Thus the 2-cascade magnetrons, Fig. 2, allow decreasing of the locking power up to -25 dB relative the output power. This allows the hundreds of W driver if the output power of 100 kW per the 2-cascade magnetron is required.

Moreover, the low phase noise and precisely-stable carrier frequency are highly-important for RF sources intended for compensation of SR at minimized emittance.

The parameters were tested with experimental model utilizing a single CW, 2.45 GHz, 1 kW magnetron frequency-locked at  $P_{Lock} = -13$  dB. The magnetron was fed by a commercial Switch-Mode Power Supply (S-MPS). The phase noise spectra of the magnetron and the locking signal are plotted in Fig. 5.

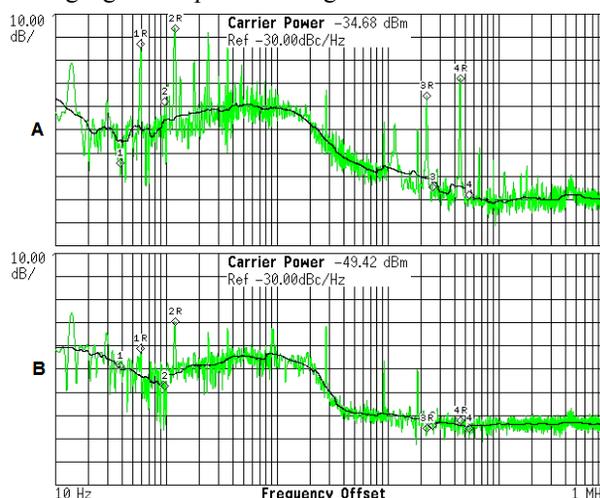


Figure 5: Trace A- phase noise of the frequency-locked magnetron fed by switch-mode power supply at  $P_{Lock} = -13$  dB. Trace B shows the phase noise of the locking signal. Black traces show averaged phase noises.

The phase noise peaks are sidebands caused by S-MPS of the magnetron and S-MPS of the TWT amplifier.

The carrier frequency spectra of the locking signal and magnetron fed by the S-MPS are shown in Fig. 6.

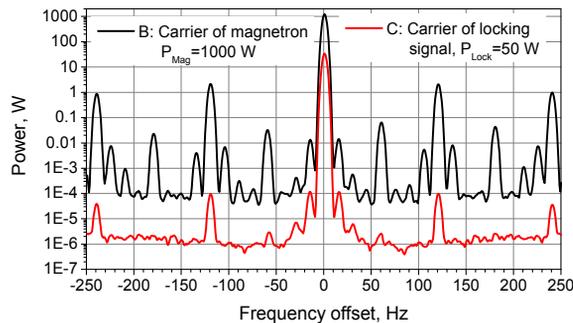


Figure 6: Measured offsets of carrier frequency of the locking signal and the frequency-locked magnetron fed by an S-MPS.

Figures 5, 6 demonstrate the phase noise  $\leq -70$  dBc of the magnetron at the carrier frequency offset in the range of (10 Hz-1 MHz) and precisely stable carrier frequency for the magnetron frequency-locked at  $P_{Lock} = -13$  dB in spite of noisy magnetron power supply. It indicates that the magnetron transmitters fed by industrial S-MPS will satisfy requirements for the SR compensation.

## WIDE-BAND POWER CONTROL IN THE MAGNETRON TRANSMITTERS

A power control of the RF sources feeding the SRF cavities is necessary to eliminate (using a feedback within closed loops) the parasitic amplitude modulation resulted in the cavities from mechanical noises (microphonics, etc.). A simple concept of the wide-band power control in magnetron transmitters for any load impedance is based on two identical 2-cascade magnetrons combined in power by a 3-dB hybrid, [7]. Control of a phase difference in inputs of the magnetrons combined in power by the hybrid realizes the vector control of the combined power allowing varying it in a wide range: approximately from sum of powers to 0.

In this case the power control is reduced to control by the phase difference, i.e., to the phase control, which has, as it is shown above, a wide bandwidth. This was verified in experiments with two single 2.45 GHz magnetrons injection-locked at the same frequency, [3].

A novel method of the amplitude control in a SRF cavity fed by a magnetron frequency-locked by phase-modulated signals was recently proposed and verified in experiments with a 2.45 GHz single-cell SRF cavity, [4]. The method was realized with a single CW, 1 kW magnetron, frequency-locked by phase-modulated signal.

Varying depth of the phase modulation one can control amplitude at the carrier frequency according to eq. (3):

$$A_c(t) = A_0 J_0(\beta) \cos(\omega_{PM} t). \quad (3)$$

Here:  $J_0(\beta)$  is the first kind, zero-order Bessel function,  $\beta$  is the phase modulation magnitude (in radians),  $\omega_{PM}$  is

the angular frequency of the phase modulation. The phase modulation frequency of 300 kHz was chosen to keep sidebands far away from the carrier frequency. In this case they can't perturb oscillation in the very narrow-band single SRF cavity. Power of sideband reflected from the SRF cavity passing through ferrite circulator is damped in matched load. Note: to change amplitude at the carrier in 1.5-2 times one need, according to (3), providing phase modulation with magnitude  $\approx 1.2-1.5$  radians.

The experiments with a single 2.45 GHz magnetron demonstrated deviations of the field in the SRF cavity of 0.26 degrees rms and 0.3%, rms, in phase and amplitude, respectively, using a closed feedback loops at a Low Level RF controller. The results are best for now.

The novel method of power control may simplify the transmitters for SRF cavities and save a cost, but a deep wideband phase modulation may require higher locking power. Choice of the method of the power control with transmitters utilizing 2-cascade magnetrons frequency-locked by phase-modulated signals may be determined by experimental tests with real multi-cell SRF cavities.

## SUMMARY

The RF transmitters based on 2-cascade magnetrons, frequency-locked by signals phase-modulated in wide-band, are acceptable for a dynamic control in phase and power at precisely-stable carrier frequency and low phase noise. Experimental modelling of the transmitters with CW, 2.45 GHz, 1 kW magnetrons verified adequacy of the transmitters features to requirements of precise stabilization of phase and amplitude of the RF field in SRF cavities. Higher efficiency and lower capital and maintenance costs of the magnetron transmitters makes them attractive for various applications in the MEIC Project especially as 100-200 kW precisely-controlled RF sources for compensation of SR losses, the more that the standard industrial CW magnetrons in this range of power, being prototypes of magnetrons for the transmitters, are well within current manufacturer capabilities.

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