MAGNETRON RF SOURCES FOR STATE OF THE ART ACCELERATORS

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MAGNETRONS

► The magnetrons are electron oscillators operating at crossed electric and magnetic fields in range from hundreds of MHz to tens of GHz in CW or in pulsed mode; they can be used to feed RF cavities.

► Power of standard magnetrons in pulsed mode is up to 10 MW, at pulse duration of a few μs, while power of relativistic magnetrons is more than 3 GW at pulse duration of hundreds ns, [1].

► CW standard L-band magnetrons for industrial application provide output power up to 150 kW, while there is a project for development of CW, 1 MW, 200 MHz magnetron, [2].

► Efficiency of magnetrons is highest in comparison with generators based on traditional RF amplifiers (klystrons, IOTs, solid-state amplifiers); cost of unit of power is lower.

► Cost of power unit of RF sources based on magnetrons, is a few times less than the cost obtained by klystrons, Inductive Output Tubes (IOTs) and solid-state amplifiers, [3].

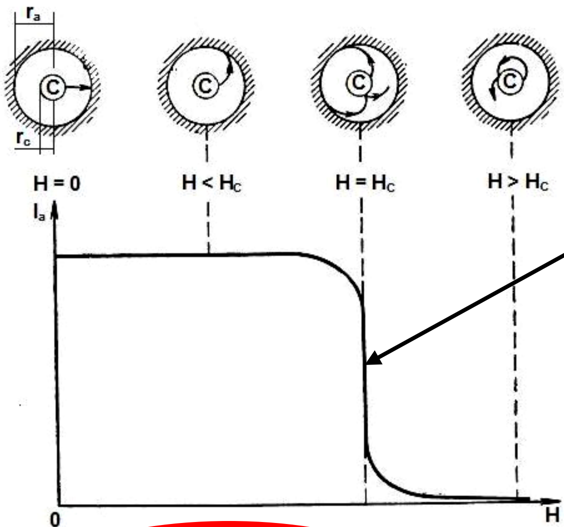
Comparative costs of RF power unit for various sources at power of tens to hundreds of kW and frequency ≥ 650 MHz [4]:

- ► Industrial CW magnetrons: $ 1 per W,
- ► CW klystrons: ~ $ 5 per W,
- ► IOTs: ~ $ 10 per W
- ► Solid-state amplifiers: $ 10-16 per W

Comparative costs of magnetron and klystron RF sources for Superconducting Proton Linac, (SPL), CERN, [5].

20 mA beam	704 MHz	Two magnetrons per cavity	One Klystron per cavity
Tube Power	kW	220	440
Duty cycle		0.05	0.05
Tube unit cost	k£	8	140
Magnets, supplies and heater	k£	4	20
number of tubes		484	242
Tube total cost	**k£**	**5,808**	**38,720**
Circulator unit cost	k£	9	16
Circulator cost	k£	4,356	3,872
HP phase shifter unit cost	k£	0	0
Total phase shifter cost	k£	0	0
Power of drive amplifier	W	300	30
Drive amplifier unit cost	k£	3.00	0.60
Number of drive amplifiers		484	242
Drive amplifier cost	k£	1,452	145
Tube + drive + circulator cost	**k£**	**11,616**	**42,737**
Modulator unit cost	k£	50	100
Total modulator cost (Guess!)	**k£**	**24,200**	**24,200**
Tube life	yrs	2	20
Annual tube replacement cost		2904	1936
Efficency		0.88	0.67
Intalled RF power	kW	106480	106480
Power consumption	kW	6050	7946
Hours per year		4800	4800
kWh cost	k£	0.00005	0.00005
Annual electricity cost	k£	1,452	1,907
Cost after installation	**k£**	**35,816**	**66,937**
Cost after 10 years	k£	79,376	105,368

Principle of operation



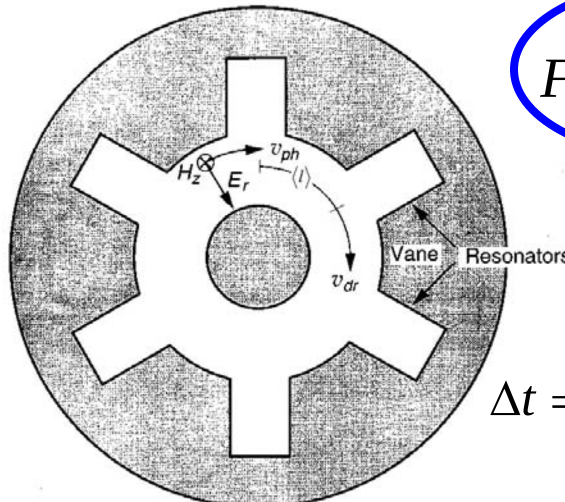
$$\frac{V}{H^2} = \frac{er_a^2}{8mc^2}\left[1-\left(\frac{r_c}{r_a}\right)^2\right]^2$$

Magnetron is a self-exciting coherent oscillator, converting DC into RF and generating at the cyclotron frequency, $\omega_C = \frac{eH}{m_e c}$.

$$F_C = \frac{m_e \cdot v^2}{R}$$

$$F_L = F_C$$

$$F_L = eE + \frac{e}{c}\left[\vec{v}\times\vec{H}\right]$$



$$\langle l \rangle = \frac{\pi(r_a + r_c)}{N}; \quad \Delta\varphi_n = \frac{2\pi \cdot n}{N};$$

$$\Delta t = \frac{\Delta\varphi_n}{2\pi} T_n = \frac{\Delta\varphi_n}{2\pi \cdot f_n} = \frac{n}{N \cdot f_n};$$

$$v_{\varphi n} = \frac{\langle l \rangle}{\Delta t} = \frac{\pi(r_a + r_c)}{n} f_n.$$

In the diode: $v_{dr} = \frac{E \cdot c}{H}$.

For cylindrical geometry: $E \approx \frac{U_a}{r_a - r_c}$.

At $v_{\varphi n} = v_{dr}$:

$$U_H = \frac{\pi\left(r_a^2 - r_c^2\right)}{n \cdot c} f_n H.$$

U_H-Hartree voltage

When $U_a \geq U_H$, the Cherenkov synchronism between v_{dr} and $v_{\varphi n}$ is fulfilled.

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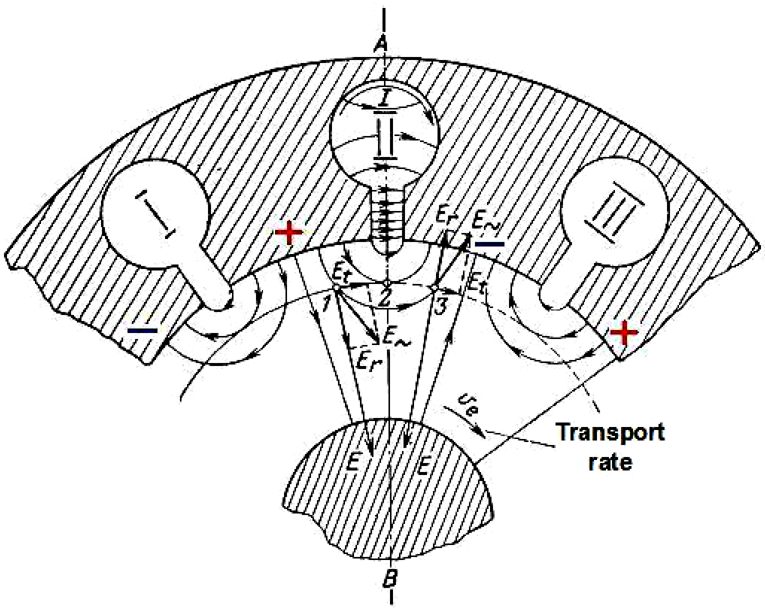
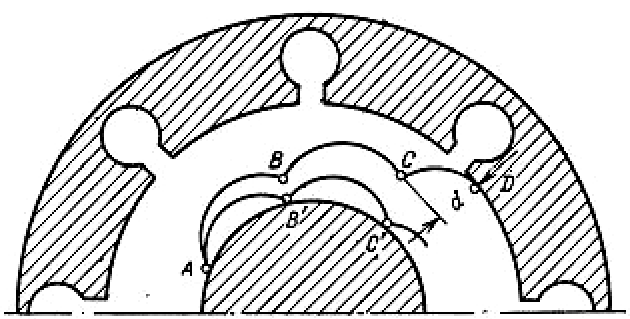
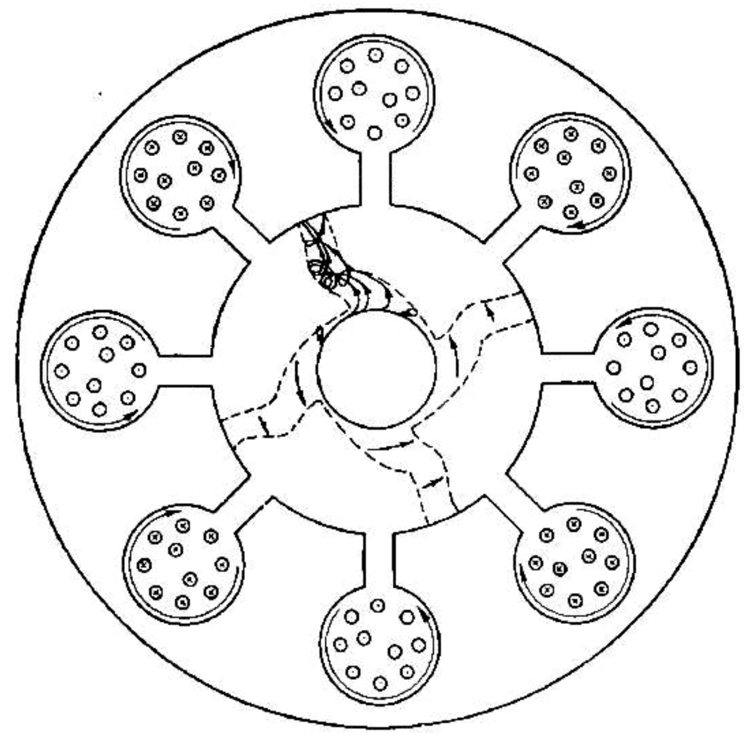
Trajectories and bunching in magnetrons

At $U_a > U_H$ the transported charge causes coherent Cherenkov generation greatly magnified by cavities.







► Magnetrons are most efficient RF sources in wide range of power and frequency

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REQUIREMENTS OF STATE OF THE ART (SUPERCONDUCTING) ACCELERATORS TO RF SOURCE

► The average RF power to feed, for example, a nine-cell, 1.3 GHz SRF cavity at the energy gain of ~20 MeV/cavity and a 1-10 mA average beam current is a few tens to a few hundreds of kW.

► Each SRF cavity has to be powered by an individual RF source, dynamically controlled by a Low Level RF (LLRF) system to prevent beam emittance growth, caused by mechanical oscillations of the SRF cavities, beam loading, dynamic cavity tuning errors and phase perturbations of the RF source.

► **RF field in each SRF cavity has to be precisely-stable (according to requirements) in phase and amplitude.**

► A concept assuming feeding of the SRF cavities by frequency and phase-locked, stabilized in power RF sources is not applicable for superconducting accelerators, since the parasitic modulations, inherent in the SRF cavities, exist even if the RF sources are ideally stable.

SOLUTION FOR RF SOURCE OF STATE OF THE ART (SUPERCONDUCTING) ACCELERATORS

► Instead of stabilization of power and phase (locking the phase) of the RF sources, operation of SRF cavities requires stabilization of the RF field in the cavities.

► The RF source intended to power the SRF cavity has to provide at precisely-stable carrier frequency a wideband dynamic phase and power control allowing to eliminate the parasitic modulations inherent in the cavity.

► A concept of magnetrons forced (frequency-locked) by a phase-modulated signal was proposed and realized, [6].

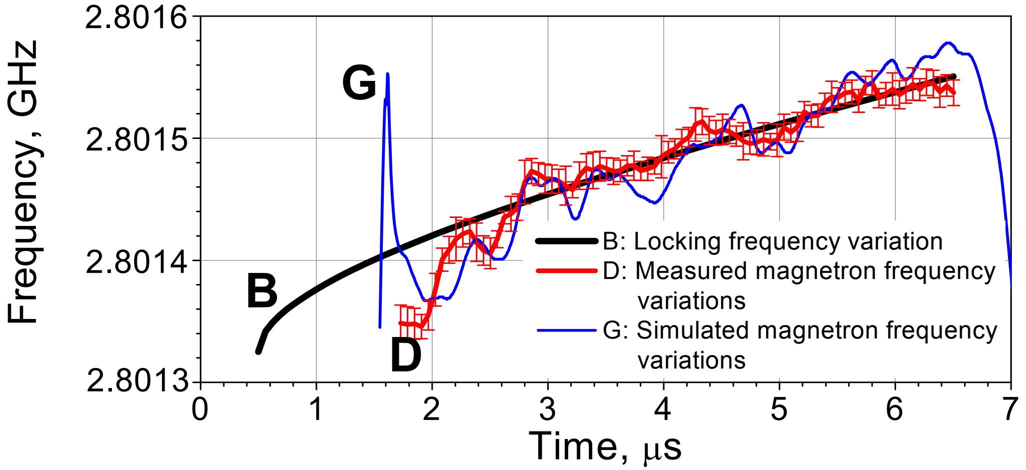
► We demonstrated wideband power control and phase control at a precisely-stable carrier frequency in models of the proposed magnetron RF source, [ibid.]. It makes possible the required dynamic control and stabilization of phase and amplitude of the accelerating field in the load, e.g. in SRF cavity.

Earlier experiments with a magnetron injection-locked by a frequency (phase)-modulated signal demonstrated that, [7-9]:

- ► Time-to-lock the magnetron is ≤1.5 μs at locking power of -18 dB.
- ► Magnetron response on frequency/phase modulated locking signal is quite linear.
- ► Phase error measured in response on the locking signal is quite small, ≤ 0.4 degree (rms).

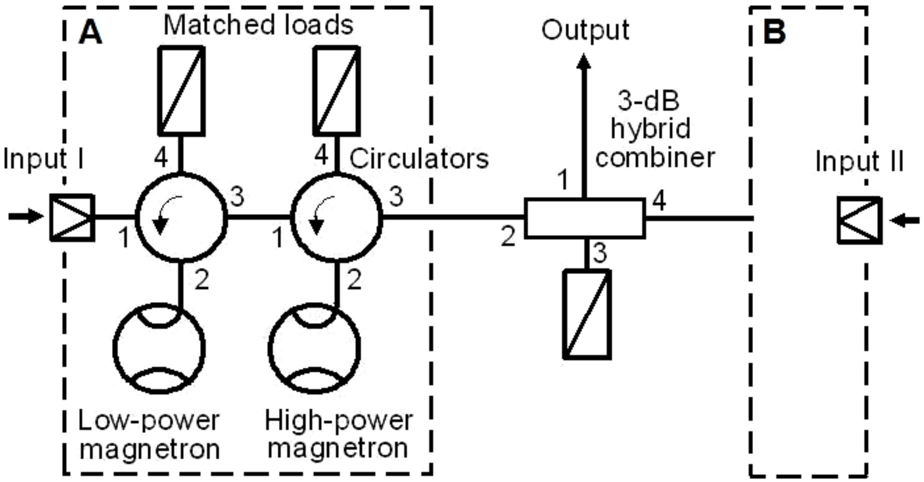
First demonstration of the frequency control of a 2.8 GHz magnetron by frequency-modulated (varied) injection-locking signal [9].

Simulated, G, and measured, D, frequency variation of the S-band magnetron, locked by a signal with varied frequency, B, at the locking power of -18 dB, [9]



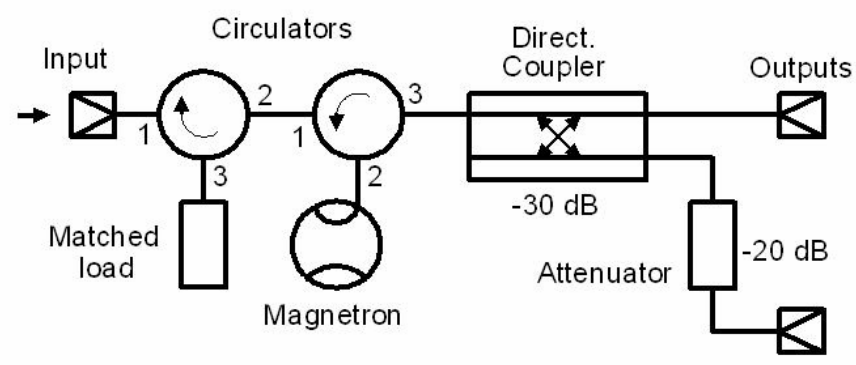
▼ ***This analysis substantiates control of magnetrons by injection-locking frequency/phase-modulated signal.***

Experimental technique and methods of the wideband control (modulation) in magnetron transmitters

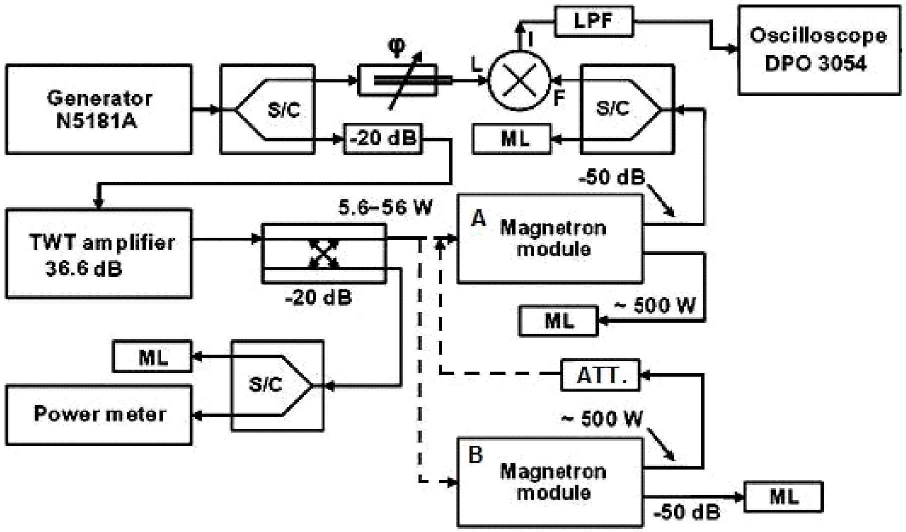


The phase modulation is provided by modulation (simultaneously and equally) of the phases at inputs of both 2-cascade magnetrons. The amplitude (power) modulation is provided at modulation by phase difference at the inputs of the 2-cascade magnetrons. The 2-cascade injection-locked magnetrons allow reducing the required locking power by 10-15 dB.

Conceptual scheme of the magnetron transmitter acceptable for wideband phase and amplitude modulation in a load, [10].

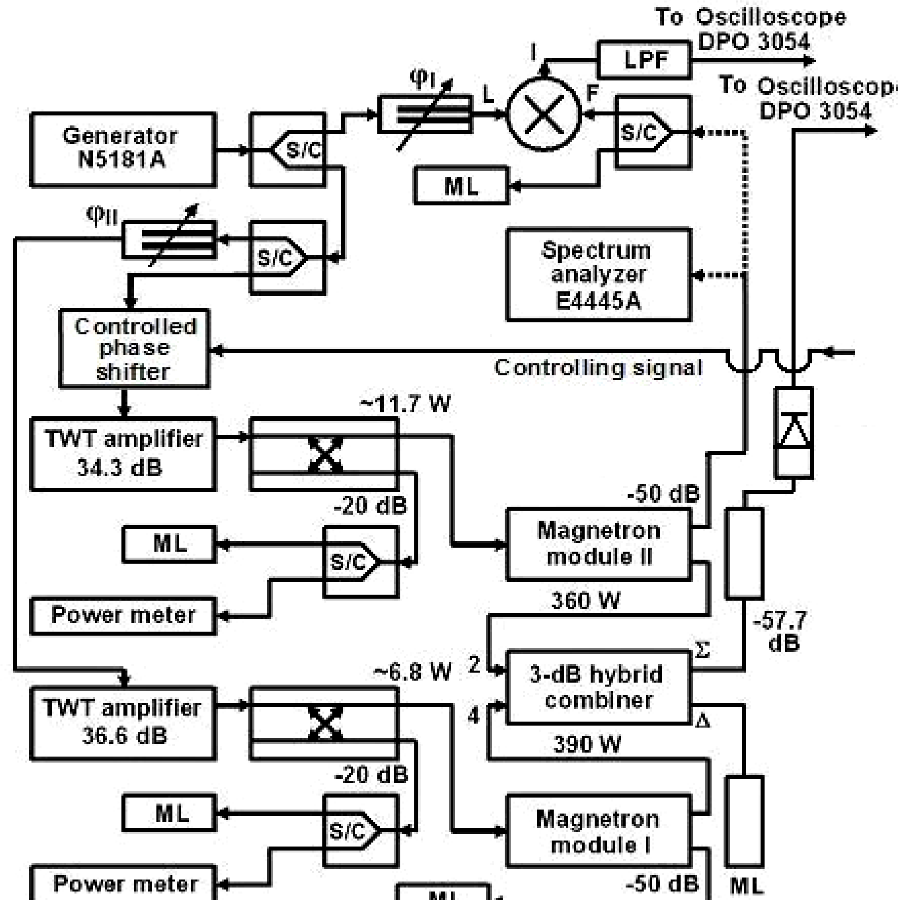


The magnetron experimental module for tests of the transmitter setup, [6].



Setup to study operation of single and 2-cascade frequency-locked magnetrons at the phase modulation, [11].

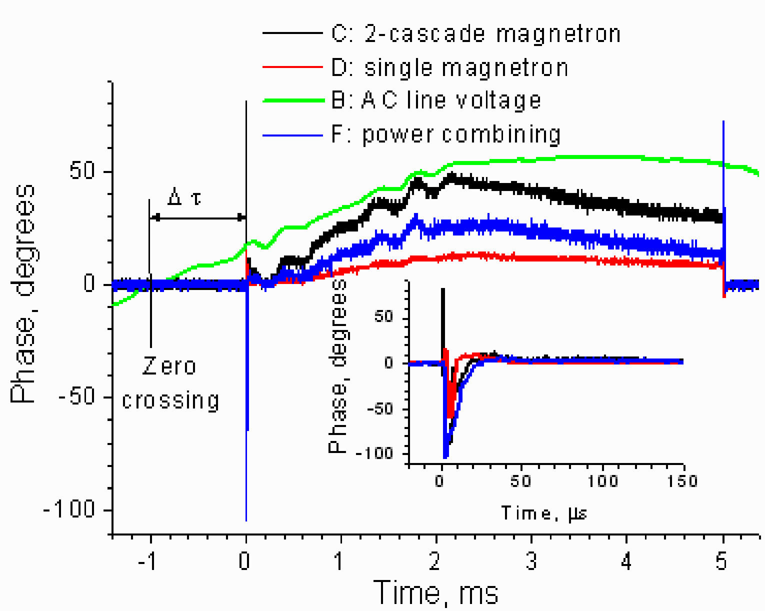
The wideband phase modulation of the frequency-locked single, 2-cascade, and magnetrons with power combining was realized at an internal phase modulation in the generator N5181A. The wideband (2-4 GHz) TWT amplifier did not distort the phase-modulated signal, frequency-locking the magnetrons.



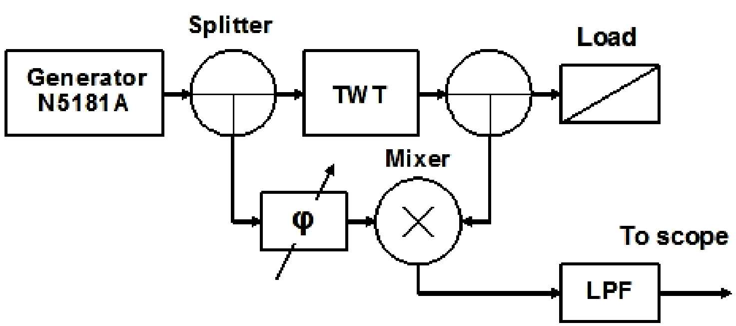
Setup for the frequency-locked magnetrons with power combining to study wideband phase and power (amplitude) modulation in the transmitter, [6].

The modulation of the phase difference in the power combining setup was realized by the controlled analogue phase shifter.

Phase noise of the frequency-locked magnetrons



Phase noise of the frequency-locked magnetrons operating in pulsed mode at various locking powers. Traces: D- P_{Lock}= -9.6 dB, F- P_{Lock}~-14 dB, C- P_{Lock}=-30 dB.



Setup to measure in CW mode the stochastic noise of the magnetron locking signal.

In pulsed mode were observed two kind of phase noise:

1. Stable from pulse-to pulse low-frequency (bandwidth << tens of kHz) phase perturbations in the magnetrons.
2. High-frequency (bandwidth > tens of kHz) stochastic phase noise.

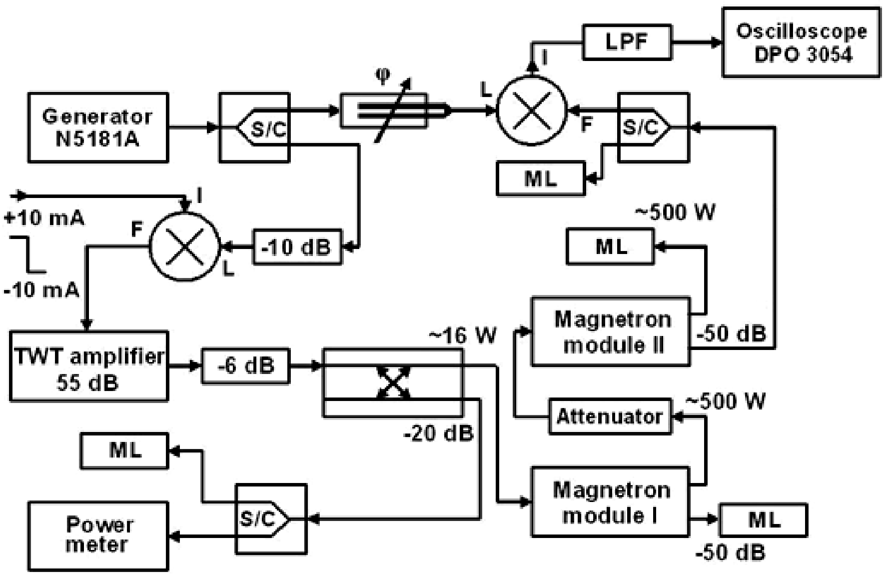
The firsts these with magnitude < 1.0 rad. result from transient processes in magnetrons. They depend on locking power, [6].

The stochastic noise magnitudes (rms) of ≈ 0.6 deg. were measured for setups with a single magnetron, 2-cascade magnetron and magnetrons with power combining.
In fact, the same is magnitude of stochastic noise of the frequency-locking signal.

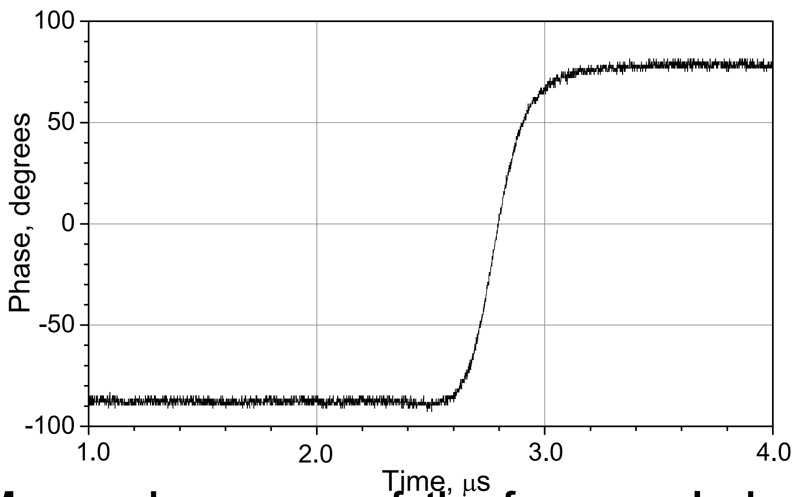
One can expect that the own stochastic noise of the injection-locked magnetrons does not exceeds a tenth of a degree.

It is promising for precise stabilization of the RF field phase and amplitude, e.g. for the MEIC electron cooler.

Response of magnetrons on a fast phase flip



Setup to measure response of 2-cascade magnetron on a fast phase flip



Measured response of the frequency-locked magnetron on a fast 180 degrees phase flip measured at ratio of the output power to locking power of 26.5 dB, [6]. Tolerance of measurements by the phase detector is about of ±10 deg.

This feature of the frequency-locked magnetrons can be used to feed the deflecting cavities for a **scanning synchronization of colliding bunches for MEIC project**.

Regime of a wideband phase-amplitude modulation in a magnetron transmitter with a phase control

The transfer function phase characteristics of the magnetrons were determined measuring angle θ of rotation of phasor of voltage in the magnetron output wave, relatively phasor of the frequency-locking phase-modulated signal, [6].

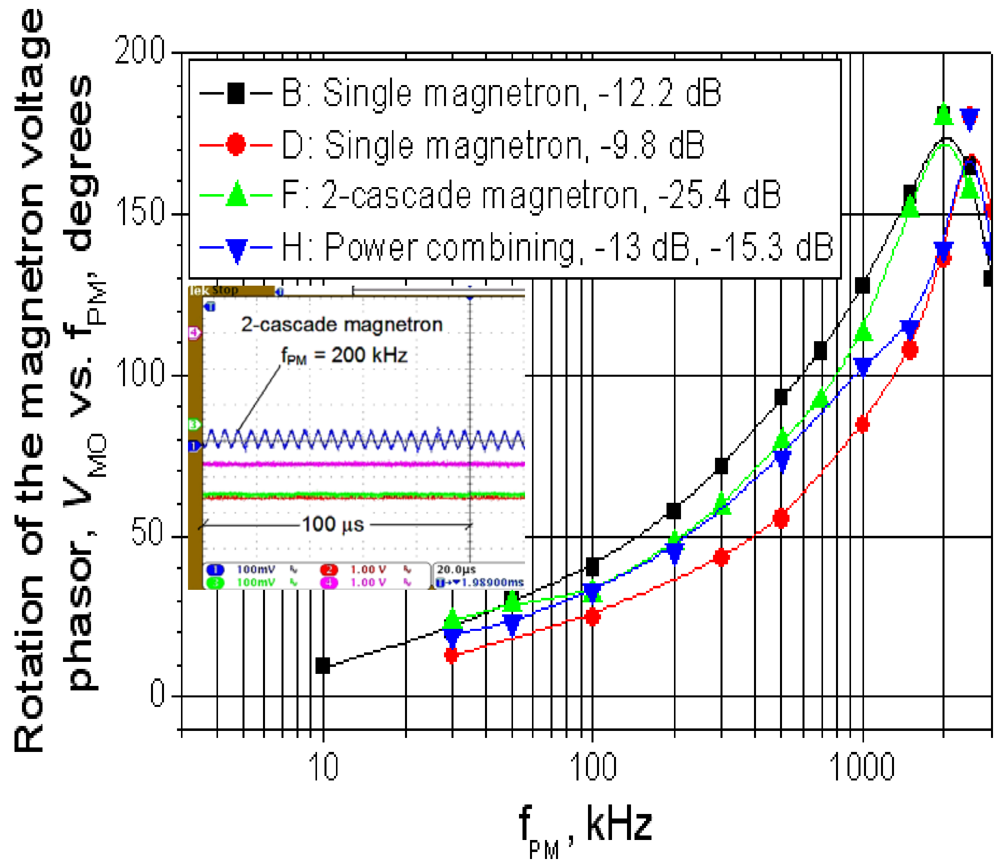
The angle was determined as:

$\theta \cong a\cos(1 - V_O / V_{PM})$, or

$\theta \cong a\sin(V_O / V_{PM} - 1) + \pi/2$

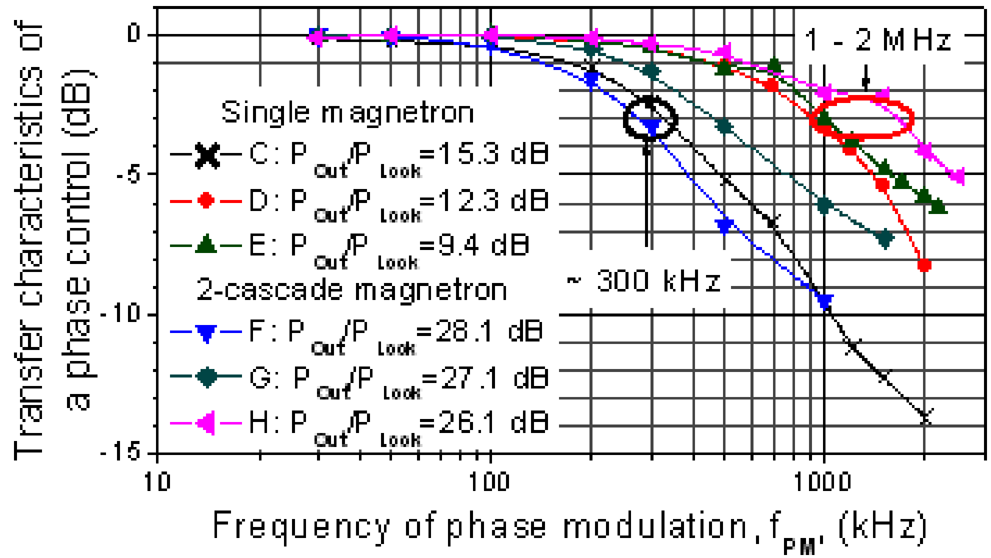
at $V_O \leq V_{PM}$ and $V_O > V_{PM}$, respectively

Here: V_O is the voltage of the harmonic signal measured at output of the phase detector, V_{PM} is the voltage, corresponding used magnitude of the phase modulation of 20 deg.



Angle of rotation of the phasor of voltage in the wave at output of the frequency-locked magnetrons vs. f_{PM}. The inset shows magnetron phase response at f_{PM}=200 kHz measured by phase detector.

The transfer function magnitude characteristics at the phase modulation of the frequency-locking signal were measured for single and 2-cascade magnetrons at low magnitude (70 mrad. ≈ 4 deg.) of the modulating signal.
The measurements were performed by the Agilent MXA N9020A Signal Analyzer in the phase modulation domain, [6].
Plotted the transfer function magnitude characteristics (rms values) were averaged over 8 pulses for the injection-locked single 2M219J magnetron and the 2-cascade magnetron setup.

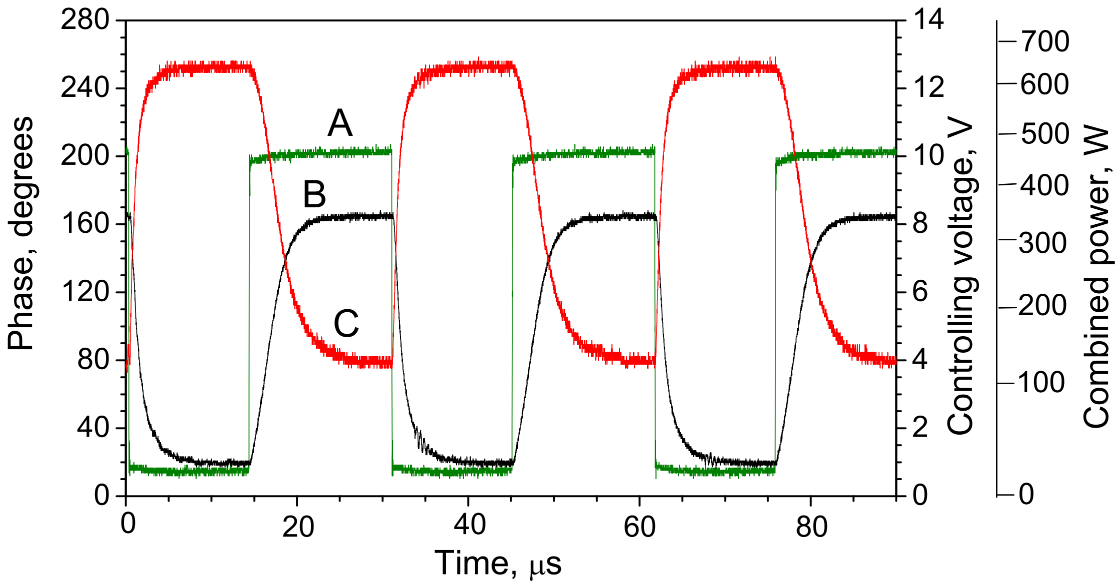


Transfer function magnitude characteristics (rms values) at the phase modulation measured in phase modulation domain with single and 2-cascade injection-locked magnetrons at various values of the locking signals. Black and red ovals show the f_{PM} cutoff at -3 dB level.

Suppression of parasitic phase modulation, K_P, at the frequency f_P in dB by a phase feedback loop in LLRF controller with integral gain I one estimates as: $K_P \approx 20 \cdot \log(I/2\pi \cdot f_P)$. For f_P=60 Hz, I =1.2·10^7 rad./s, $K_P \approx 90$ dB.

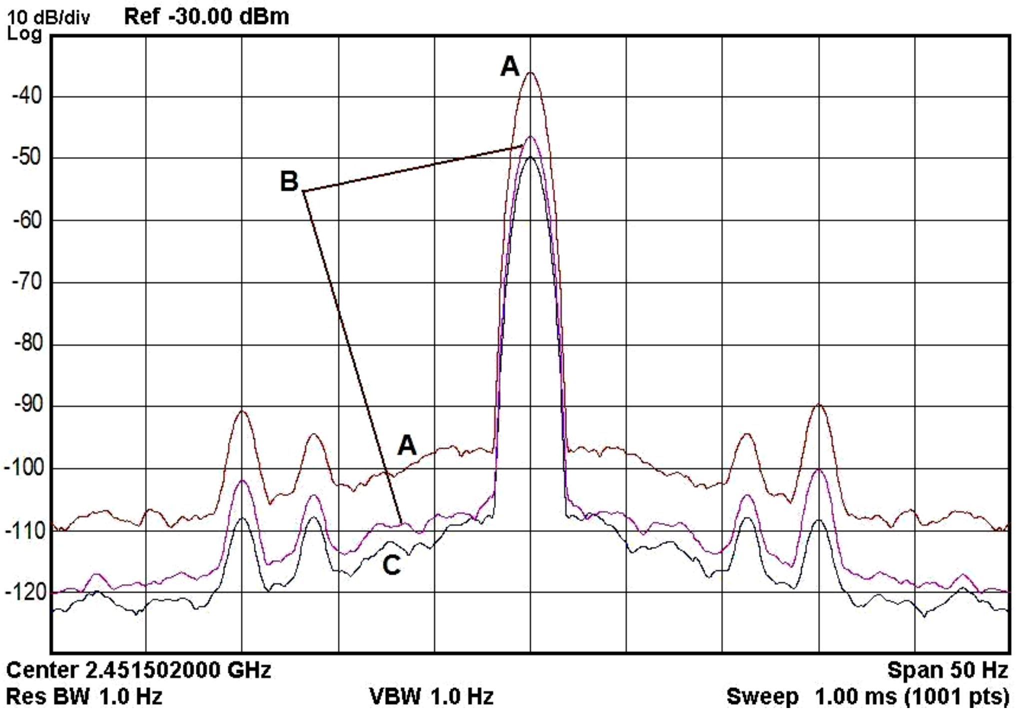
Amplitude (power) modulation of the frequency-locked magnetrons with power combining.

Realized by modulation of the phase difference in the setup 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 by a calibrated detector at port "Σ" of the hybrid combiner at the phase shifter pulsed voltage control, second right scale, [6].

Carrier frequency spectra of the magnetron injection-locked by phase-modulated signal



Carrier frequency spectra of the magnetron injection-locked by a signal without phase modulation, trace A, and with the phase modulation, at f_{PM}=2 MHz, and magnitude of the modulation of 3 radians, trace B. Trace C shows the carrier frequency spectrum of the locking system (N5181A generator and TWT amplifier) without the phase modulation. Scales in vertical and horizontal are: 10 dB/div and 5 Hz/div, respectively.

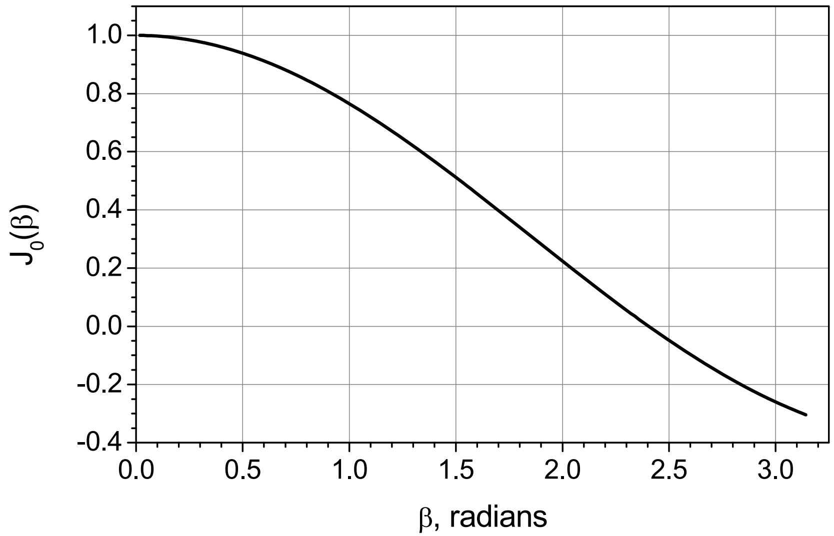
The measurements, [6], at the resolution bandwidth of 1.0 Hz were performed by the Agilent MXA N9020A Signal Analyzer using a 2.45 GHz, 1 kW magnetron, operating in CW mode at locking power of -13.4 dB, output power of ~ 850 W, carrier frequency of the locking signal of 2.451502 GHz.

Phase modulation at a narrow-band resonant load

Recently was checked capability of modulation of power in a narrow-band load (SRF cavity) fed by a CW magnetron, injection-locked by a phase-modulated (PM) signal, [12]. The novel method is based on precisely-stable carrier frequency at the PM. A 100-500 kHz frequencies of the PM were chosen in this experiment. The phase modulation causes redistribution of power in sidebands and at carrier frequency resulting in modulation of amplitude at the carrier frequency in the load, $A_c(t)$:

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

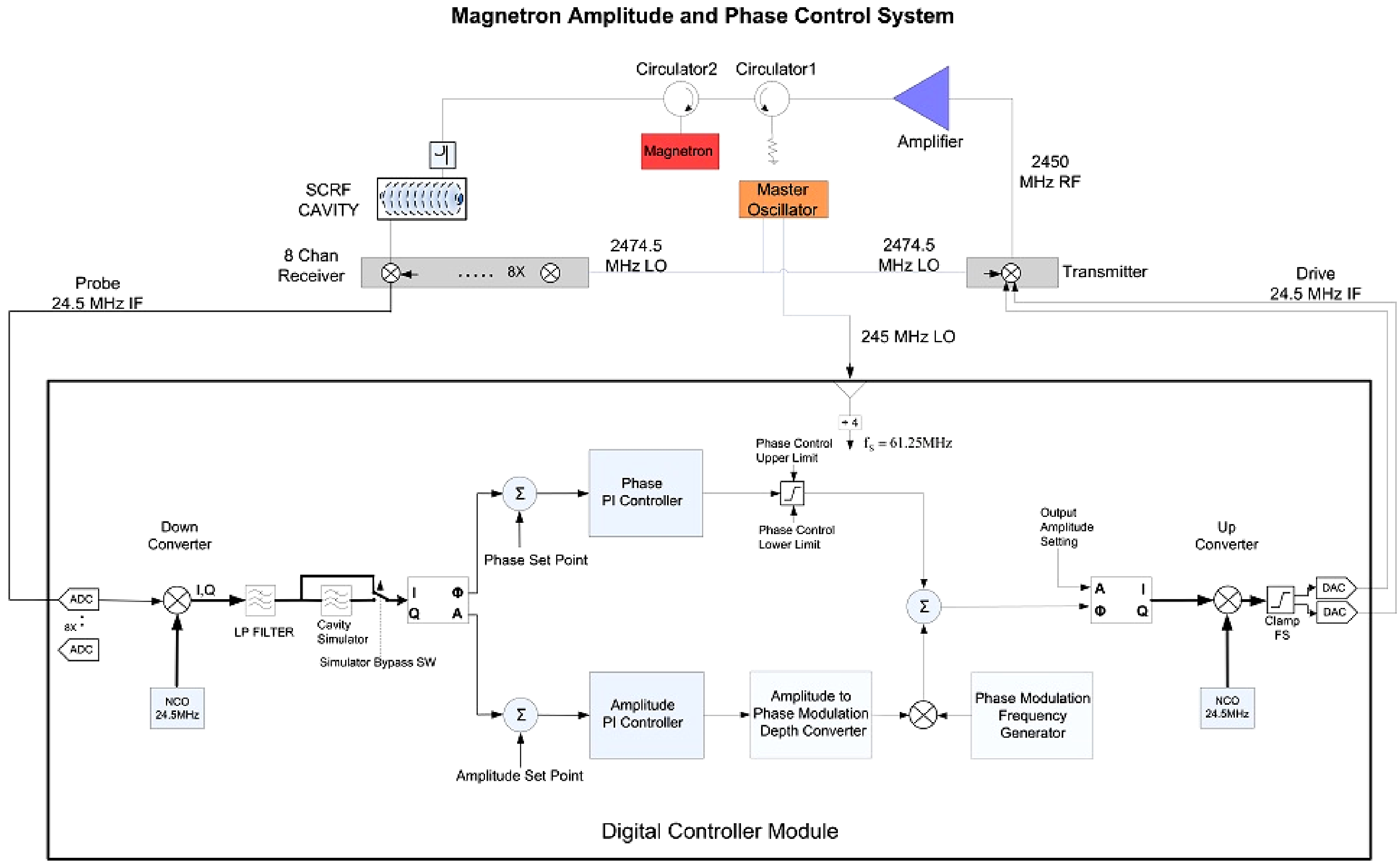
Here: $J_0(\beta)$ is the zero-order first kind Bessel function, β is the phase modulation magnitude (in radians), ω_{PM} is angular frequency of the phase modulation.



$J_0(\beta)$ vs. β

Because of the narrow bandwidth of the SRF cavity, the PM sidebands, which may start at a PM frequency offset, are reflected by the cavity back to a circulator and to an absorptive load, [12], leaving only the desired amplitude regulated carrier and close to carrier information required to drive and regulate the cavity field.

Wide-band phase and power control by phase modulation at a narrow-band resonant load



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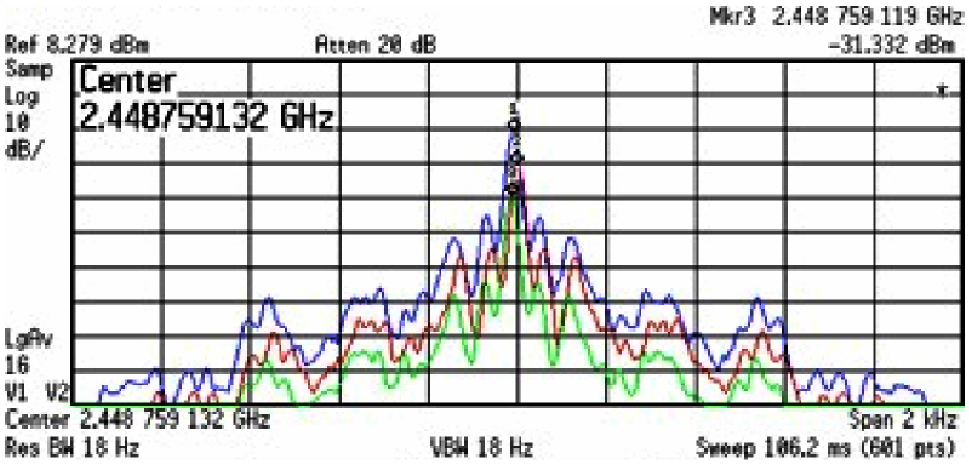
The test of the method was performed in a vertical cryostat of A0 Fermilab facility with a 2.45 GHz SRF cavity barrowed from JLab. The single magnetron fed by the switch mode SM 445G HV PS, operating as a current source, generated RF power was of 500 W. The power after attenuation resulted in the cavity drive signal of 1.7 W. The modulation frequency for the PM was 300 kHz.



Cavity probe spectra.
Dynamic range : 0 dB (blue), 3 dB (red), 6 dB (green), steps in the amplitude feed back loop.

Applying this novel method of phase and power control to a 2.45 GHz superconducting cavity was demonstrated very high stability of the cavity RF field in amplitude, 0.3%, rms, and in phase, 0.26 degrees, rms, [12].

SUMMARY

- ► Proof-of principle of a wideband phase control at precisely-stable carrier frequency by phase modulation of the signal frequency-locking the magnetrons was demonstrated in experiments with magnetrons operating in CW and pulsed modes.
- ► Methods of tests of capability of magnetrons for the wideband phase control were developed and applied for measurements.
- ► Proof-of-principle of a concept of high-power magnetron transmitter based on 2-cascade magnetrons with power combining by a 3 dB hybrid, allowing the wideband phase and power control at any load impedance and acceptable to feed SRF cavities was demonstrated by experimental and numerical models.
- ► Proof-of-principle of power control in a narrow-band load (SRF cavity), based on wide-band phase modulation of the signal, frequency-locking magnetron, was demonstrated in experiments with 2.45 GHz SRF cavity.
- ► A LLRF controller with a closed feedback loop utilizing the wideband phase modulation of the frequency-locking signal to stabilize phase and amplitude of RF field in the SRF cavity was developed and tested.
- ► Stability of the RF field in 2.45 GHz SRF cavity in phase, 0.26 deg. rms, and in amplitude, 0.3% rms, respectively, was reached at the dynamic control using wide-band modulation of the frequency-locking signal.

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Thank you!