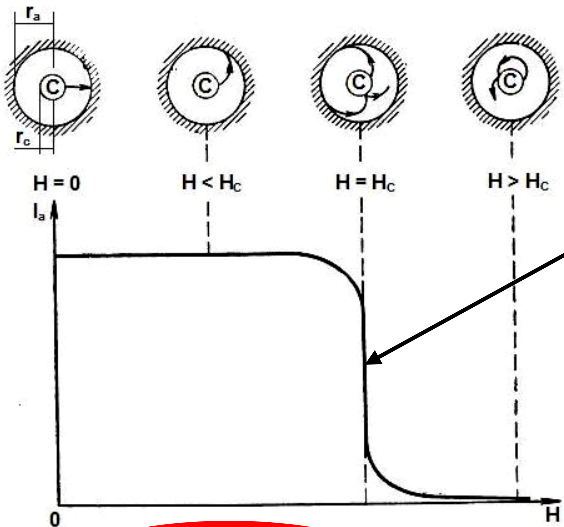
Application of magnetrons for intensity-frontier superconducting linacs

MAGNETRONS



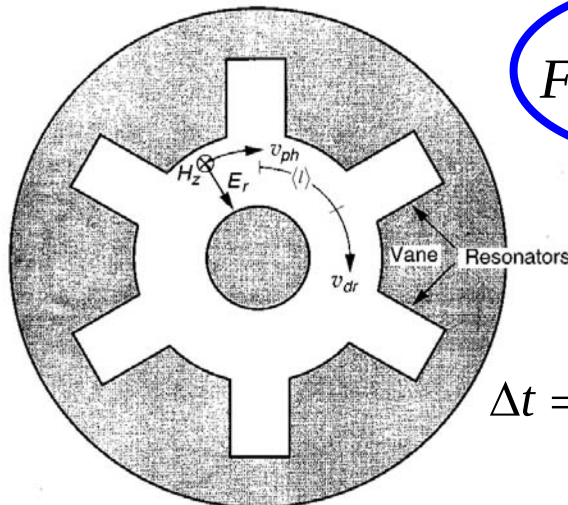
$$\frac{V}{H^2} = \frac{e r_a^2}{8mc^2}\left[1-\left(\frac{r_c}{r_a}\right)^2\right]^2$$

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

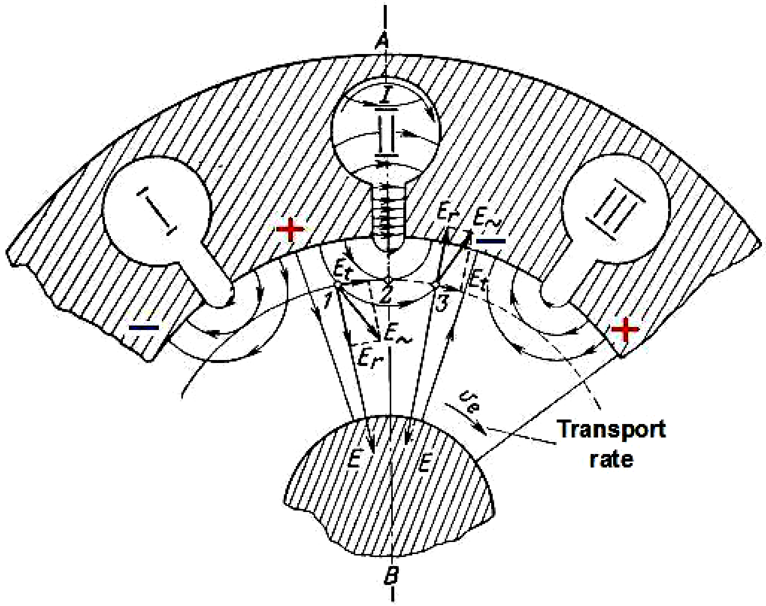
$$U_H = \frac{\pi\left(r_a^2 - r_c^2\right)}{n \cdot c} f_n H.$$

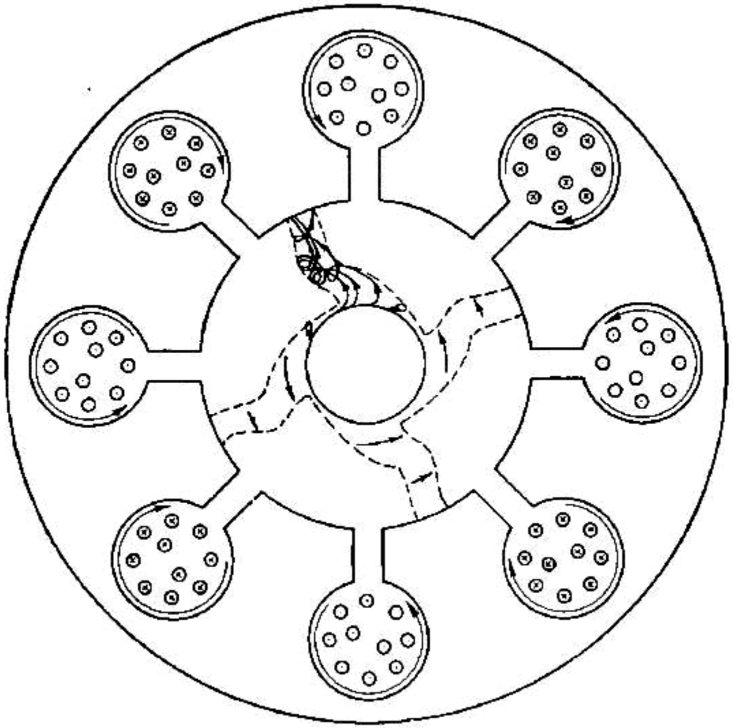
U_H-Hartree voltage

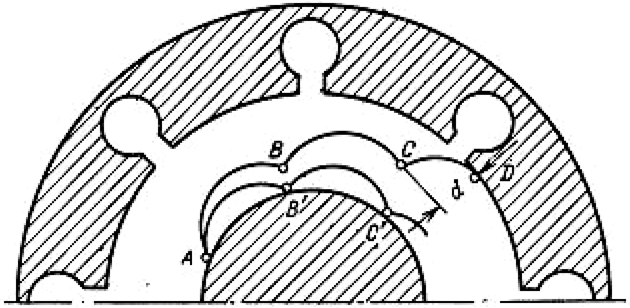
When $U_a \geq U_H$, the Cherenkov synchronism between v_{dr} and $v_{\varphi n}$ is fulfilled.

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

Noise of magnetrons

Two components contribute in the magnetron stochastic noise:

- ► Shot noise of the magnetron current,
- ► Thermal noise of the magnetron current.

Shot noise of the magnetron current, averaged over the magnetron cavity filling time, τ, causes noise in radiation.

$\tau \sim Q_L/\pi \cdot f \sim 13$ ns. At $I \sim 0.3$ A,

the transported charge $\Delta q \sim I \cdot \tau \sim 3.9$ nC.

The relative fluctuation of the charge

is: $$\sqrt{\frac{\Delta q}{e}} \cdot \left(\frac{\Delta q}{e}\right)^{-1} \sim 6.4 \cdot 10^{-6}$$

Thermal noise rms voltage is:

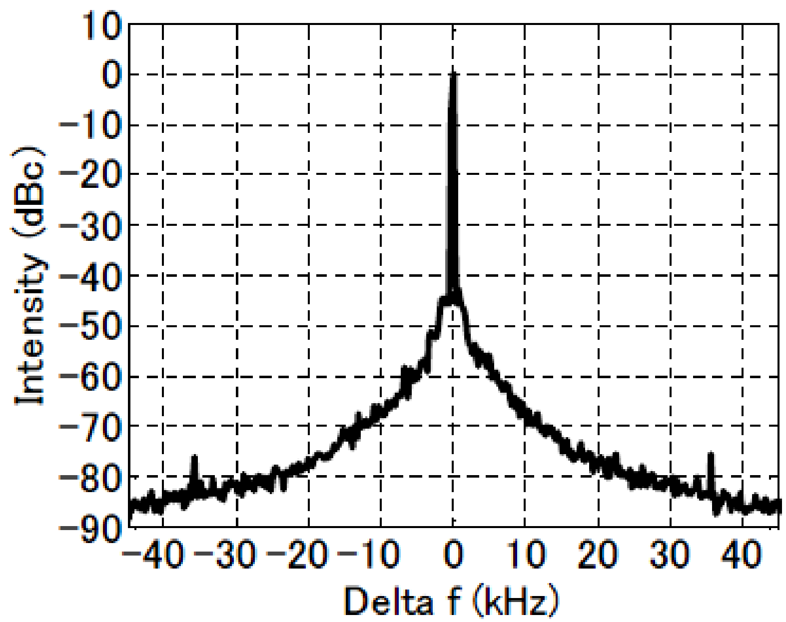
$$v_n = \sqrt{\bar{v}_n^2}\sqrt{\Delta f} = \sqrt{4k_B T R_{Sh} \Delta f} \sim 1.8 \cdot 10^{-4}\ \text{V}.$$

Here: $\Delta f \sim 0.35/\tau \sim 26.9$ MHz, $R_{Sh} \sim 8.7$ k,

so the thermal noise power,

$P_{Th} = v_n^2/R_{Sh} \leq 3.8 \cdot 10^{-12}$ W <-140 dBm.

► Magnetrons are low-noise devices.



The oscillation spectrum of a 2.45GHz oven magnetron in the injection locking operation, [1].

Application of magnetrons in accelerators

As self-excited inexpensive RF sources mostly for S-band and X-band low-energy pulsed electron linacs and microtrons:

Mark-I: 6 MeV linac powered by magnetrons (1948),
medical linacs, classical microtrons, etc.

Well known drawbacks limited utilization of magnetrons; they are used mostly in single-cavity / single-section accelerators.

► Free run frequency pulse-to–pulse is not stable enough since Q_{ext} of the magnetrons is ≈ 100-200.

► Frequency instability caused by the change in the current of the magnetron (frequency pushing) is inherent in the magnetron.

► Frequency instability caused by the change of the reflected signal (frequency pulling) is inherent in the magnetron.

Magnetrons can be synchronized and stabilized, but…

Klystrons were chosen as preferable RF sources for multi-cavity accelerators

► However, cost of RF sources based on magnetrons, is in few times less than the cost with klystrons, Inductive Output Tubes, (IOTs), and solid-state amplifiers, [2, 3].

Costs of RF power for various sources at power of tens to hundreds kW and frequency ≥ 650 MHz are:

- ► Industrial CW magnetron RF sources: $ 1 per W,
- ► CW klystrons: ~ $ 5 per W,
- ► IOTs: ~ $ 10 per W
- ► Solid-state amplifiers: $ 14 per W

How to synchronize and stabilize the magnetrons properly*?*

► *We proved technology of Injection locking in "paraphasing"!*

► *We proved the "Gain" on order of 30 dB for 2-cascaded injection-locked magnetron!*

Approach of a transient process in a magnetron forced (locked) by a frequency/phase modulated signal first has been considered in [5-7]

- Consideration of a magnetron as a forced oscillator with a beam, and a cavity coupled with a waveguide. For a steady-state of the oscillator, [4]:

$$\left[\frac{d^2}{dt^2}+\frac{\omega_0}{Q_L}\cdot\frac{d}{d\,t}+\omega_0^2\cdot\right]V_C=2\cdot\frac{\omega_0}{Q_E}\cdot\frac{d\,V_F}{d\,t}+\omega_0\cdot\frac{R_{Sh}}{2\cdot Q_0}\cdot\frac{d\,I_B}{d\,t}$$

Here: Q_L, Q_0 and Q_E are the loaded cavity Q-factor, the wall loss Q-factor, and the external cavity Q-factor, respectively, ω_0 is the circular eigenfrequency, V_L and V_F are amplitudes of the oscillation in the cavity and in the forcing wave, respectively, R_{Sh} is the shunt impedance of the cavity, I_B is the amplitude of the first harmonic of the beam current.

► Averaging over (fast) oscillations in the cavity using SVEA method, [4], at:

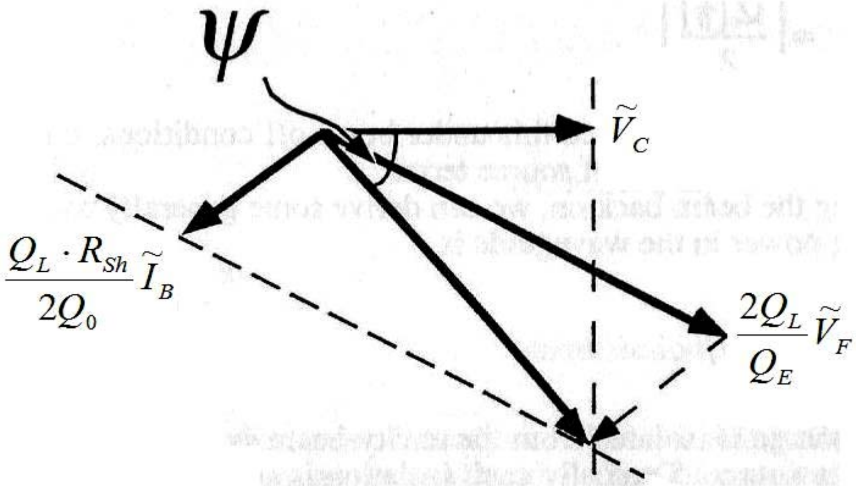
$$V_C = \tilde{V}_C(t)\cdot e^{i\omega t},\qquad V_F = \tilde{V}_F(t)\cdot e^{i\omega t},\qquad I_B = \tilde{I}_B(t)\cdot e^{i\omega t}$$ at $$\left|d\tilde{V}_C/dt\right| << \left|\omega_0 \tilde{V}_C\right|,$$

$$\left|d\tilde{I}_B/dt\right| << \left|\omega_0 \tilde{I}_B\right|,\qquad \left|d^2\tilde{V}_C/dt^2\right| << \left|\omega_0^2 V_C\right|,$$

► For a steady-state one gets equation describing a transient process in the forced oscillator, [4].

$$\frac{d\tilde{V}_C}{dt} + \frac{\omega_0}{2Q_L}(1 - i\tan\psi)\cdot\tilde{V}_C = \frac{\omega_0}{Q_E}\tilde{V}_F + \omega_0\frac{R_{Sh}}{4Q_0}\tilde{I}_B$$

Here: $\tan\psi = Q_L\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right) \approx 2Q_L\frac{(\omega_0 - \omega)}{\omega_0}$; ω is frequency of the forcing signal; ψ is the tuning angle, angle between the phasor $\tilde{V}_C$ and phasors $\tilde{V}_F$ and $\tilde{I}_B$ sum. Following [4] for a steady-state:



$$\tilde{V}_C = \cos\psi\cdot\exp(i\psi)\cdot\left(\frac{2Q_L}{Q_E}\tilde{V}_F + \frac{Q_L}{Q_E}\tilde{I}_B\right)$$

► The abridged equation describing a transient process in a forced (injection-locked) magnetron is, [5-7]:

phase pulling — phase pushing

$$\left\{\frac{d}{dt}+\frac{\omega_{0M}}{2Q_{LM}}\cdot\left(1-i\varepsilon_M\right)\right\}\tilde{V}_M=\frac{\omega_{0M}}{Q_{EM}}\cdot\tilde{V}_{FM}-\frac{\omega_{0M}}{2Q_{EM}\cdot Y_{0M}}\cdot\tilde{I}_M+\frac{\omega_{0M}}{2Q_{EM}}\cdot V_{Noise}$$

Here: $\varepsilon_M \approx 2Q_{LM}(\omega_{0M}-\omega)/\omega_{0M}$ is detuning parameter, ω is time-dependent forcing frequency, $\tilde{V}_M$ and $\tilde{V}_{FM}$ are complex amplitudes of the oscillation in the magnetron cavity and in the wave forcing the magnetron, respectively, Y_{0M} [1/Ohm] is the external waveguide conductance of the magnetron cavity, $\tilde{I}_M$ is the complex amplitude of the first harmonic of the magnetron current.

The noise source V_{Noise} is added in the magnetron equation to excite oscillations in the magnetron, [8].

$$V_{Noise}(t)=\begin{cases} V_{M0}\cdot k_{Noise}\cdot\dfrac{U_A(t)}{U_{A\_N}}\left[1-\dfrac{V_M(t)}{V_{M0}}\right] & \text{for } V_M(t)<V_{M0} \\ 0 & \text{for } V_M(t)\geq V_{M0}\end{cases}$$

Here: $V_M(t)=\left|\tilde{V}_M(t)\right|$

V_{M0} is nominal value of $\left|\tilde{V}_M\right|$

U_{A_N} is nominal magnetron anode voltage

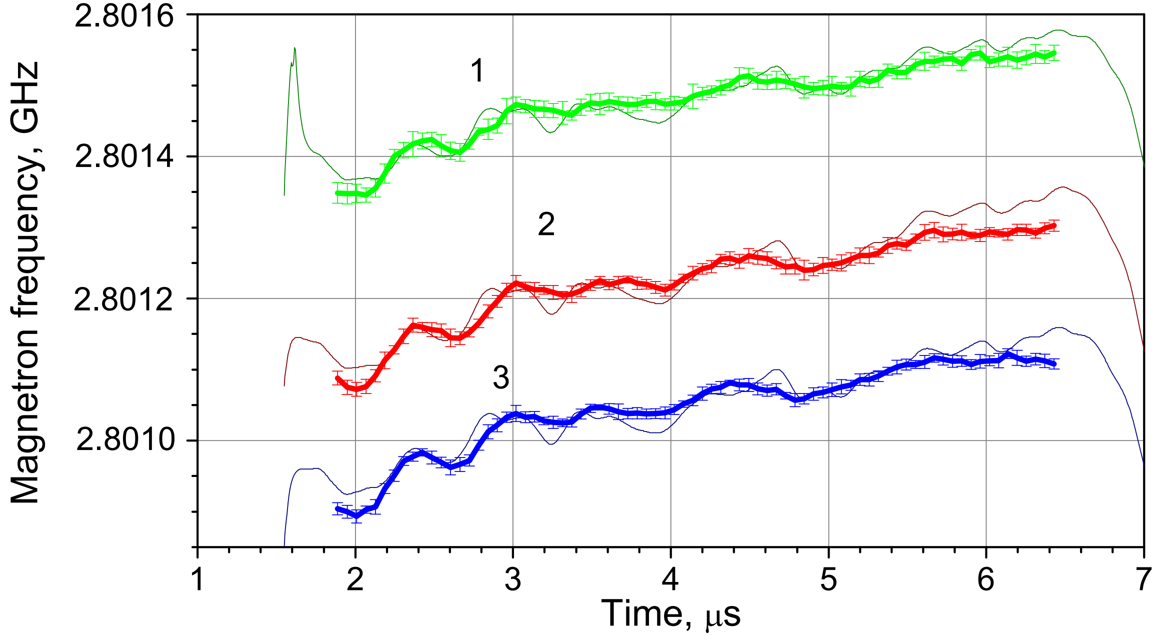
k_{Noise} is noise coefficient

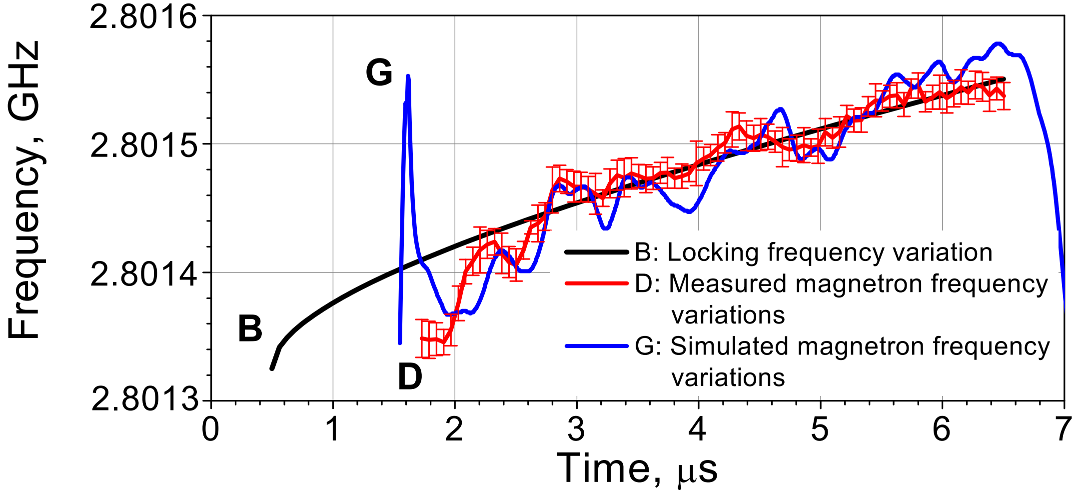
► The equation has been solved in a system in which a second equation presented voltage in the forcing wave which was reflected from the accelerating cavity loading the magnetron. The equations system was combined with equations presenting coupling between the magnetron and the loading cavity.

$$\tilde{V}_{MO} = \tilde{V}_M - \tilde{V}_{FM}, \quad \tilde{V}_{MO} = V_{MO} \cdot \exp(i \cdot \varphi_{MO}).$$

The magnetron frequency was found as: $f_{MO} = d\varphi_{MO} / 2\pi \cdot dt.$

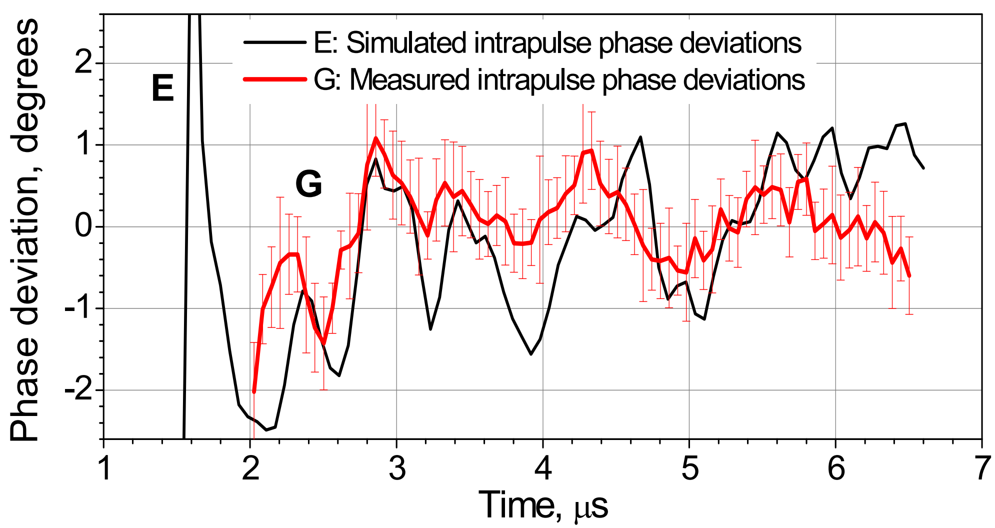
► Results were verified by measurements, [5-7].





Simulated, G, and measured, D, frequency variation of the 2.5 MW S-band magnetron locked by a signal with varying frequency, B, at power of -18 dB, [9]

Simulated, E, and measured, G, phase errors of the injection-locked magnetron, [ibid.].



Locking of 2.5 MW S-band magnetron by a frequency (phase)-modulated signal and a control of the injection-locked magnetrons

- Experiments, [6-8], verified that that the magnetron operated in injection-locked mode, [8, 10].
- The derived equation well describes control of injection-locked magnetron by frequency/phase-modulated signal or/and control by the magnetron current.
- 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 rms error measured in response on the locking signal is ≤ 0.4 degree, [9].

The features of the magnetron injection-locked by a phase-modulated signal substantiate the proposed transmitter with phase control by a feedback loop.

Control of the injection-locked conventional magnetron by current first was realized in experiments with CW, microwave oven magnetrons, [10].

MODELING OF A MAGNETRON TRANSMITTER FOR INTENSITY-FRONTIER SUPERCONDUCTING LINACS.

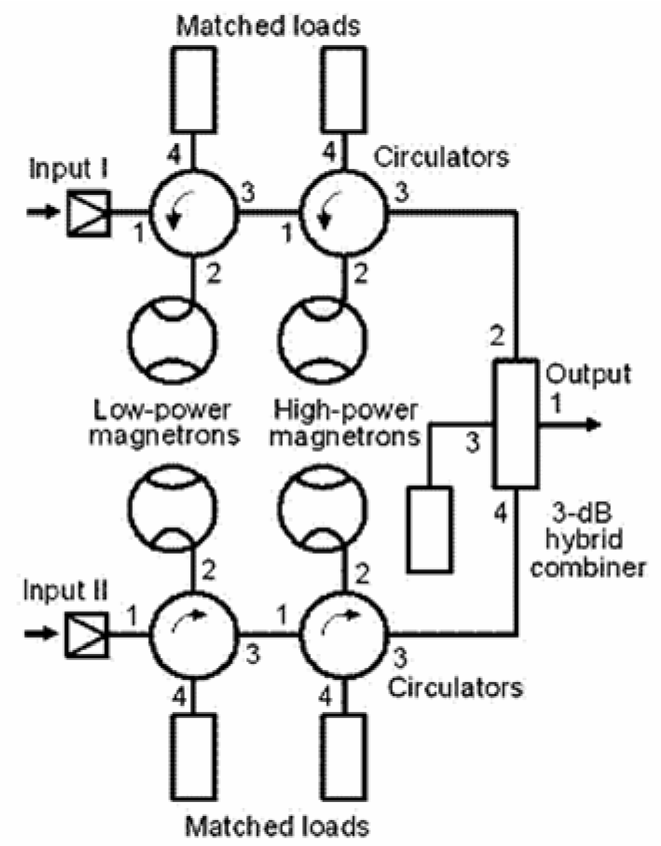
Requirements of the intensity-frontier GeV-scale superconducting proton or ion linacs to Continuous Wave (CW) RF sources:

► Deviations of the accelerating voltage in phase and amplitude less than 1 degree and 1% of nominal, respectively.

► The average RF power to feed, for example, an ILC-type 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 kW.

► Powering of each SRF cavity by an individual Low Level RF (LLRF) vector controlled RF source to prevent the beam emittance growth, [11], caused by mechanical oscillations of the SRF cavities, beam loading, dynamic cavity tuning errors, etc.

CONCEPT OF THE MAGNETRON TRANSMITTER WITH A FAST PHASE AND POWER CONTROL



The magnetron transmitter with a rapid control in power and phase, based on 2-cascade injection-locked magnetrons.

► The transmitter consists of two 2-cascade injection-locked magnetrons with outputs combined by a 3-dB hybrid, [12].

► The phase management is provided by a control of phase in both channels simultaneously, while the power management is provided by a control of phase difference on the inputs of the 2-cascade magnetrons.

TECHNIQUES FOR EXPERIMENTAL TEST OF THE MAGNETRON TRANSMITTER CONCEPT

► All features of the transmitter were studied using two CW 2.45 GHz magnetrons with output power up to 1 kW. The magnetrons were chosen to be locked at the same frequency. The magnetrons were powered by a single pulsed modulator with partial discharge of storage capacitor.

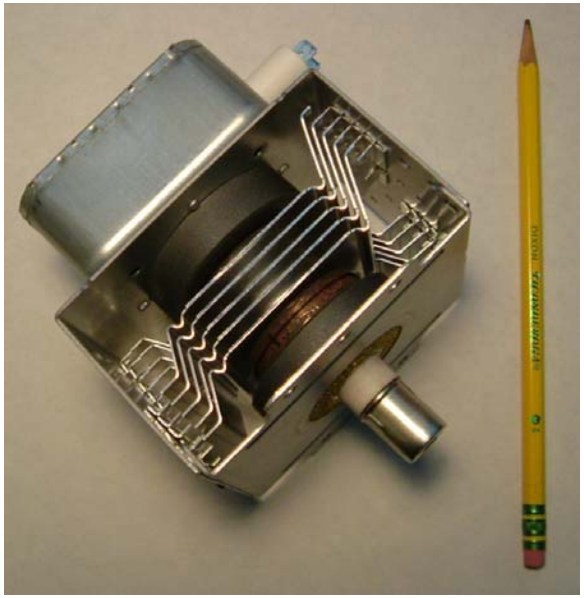
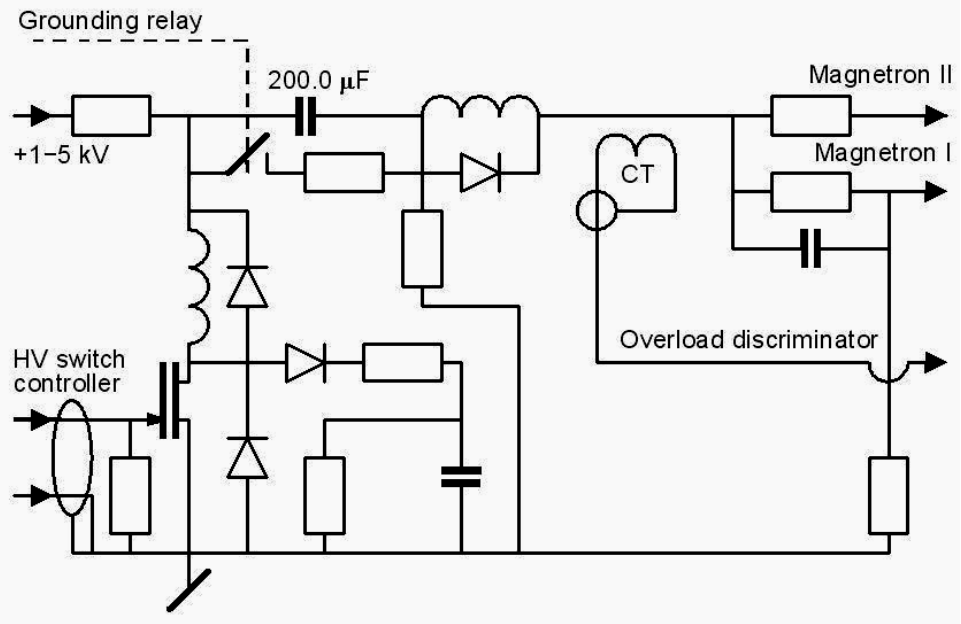


Photo of the CW, 1 kW magnetron type 2M219J

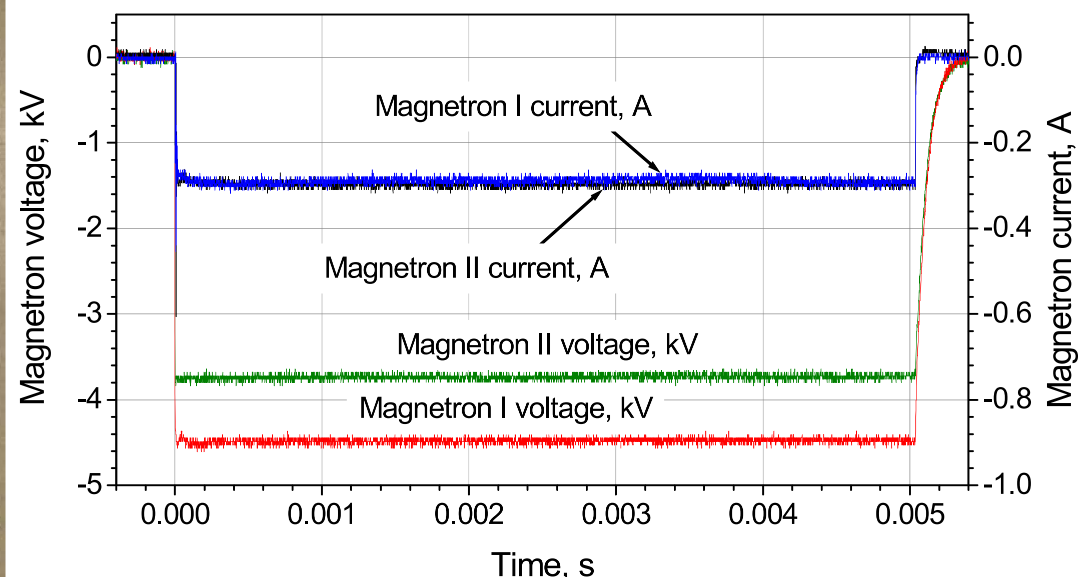


Simplified scheme of the modulator HV module

The modulator operating parameters:

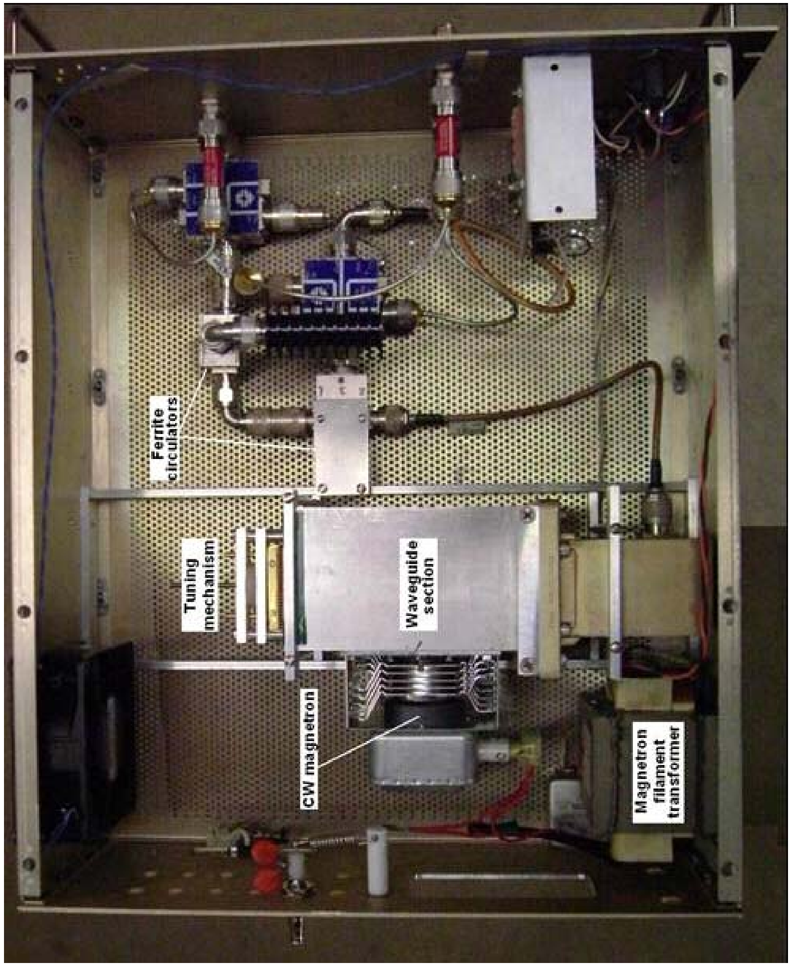
Output voltage:	U_{Out} = -(1-5) kV
Repetition rate:	0.25 Hz
Pulse duration:	2.5-15 ms
Output current:	I_{Out} = 0.3-1.0 A

Photo of the modulator HV module

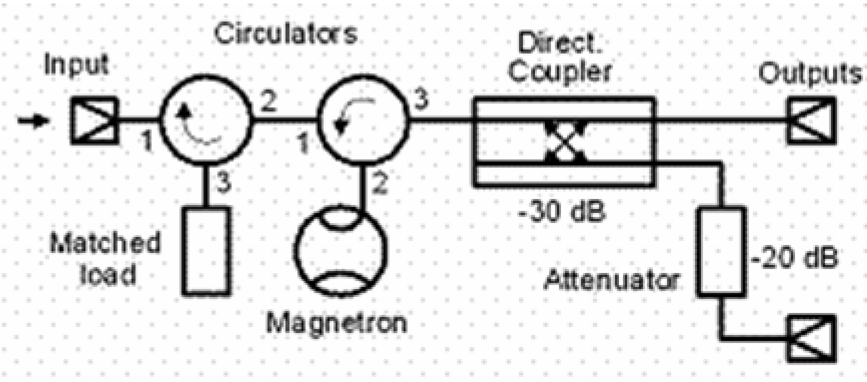


Pulse shapes of voltages and currents of the magnetrons operating simultaneously

► Features of the transmitter based on injection-locked CW magnetrons have been studied using two modules with magnetrons, 2M219J and OM75P having free run frequencies differing by ≈5.7 MHz.



Module with a CW magnetron intended to work in injection-locked mode

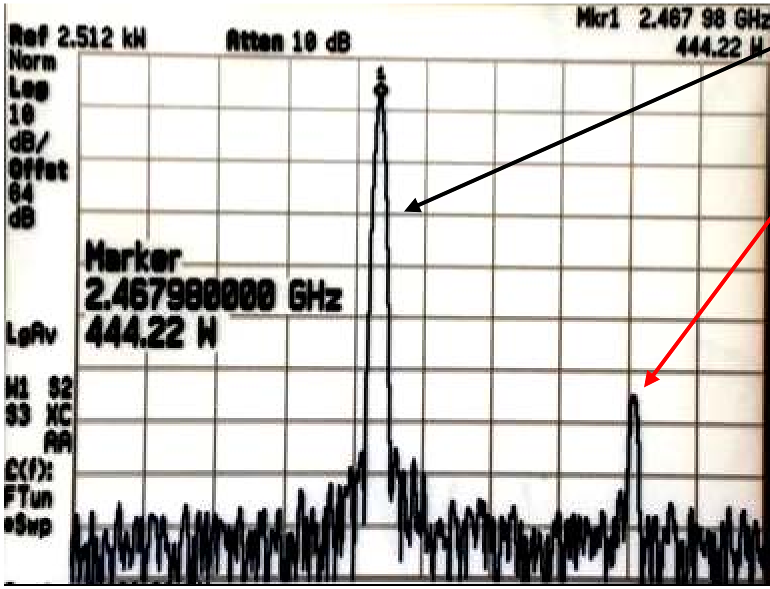


The magnetron experimental module

Simultaneous operation of the two free running magnetrons at pulse duration of 5 ms

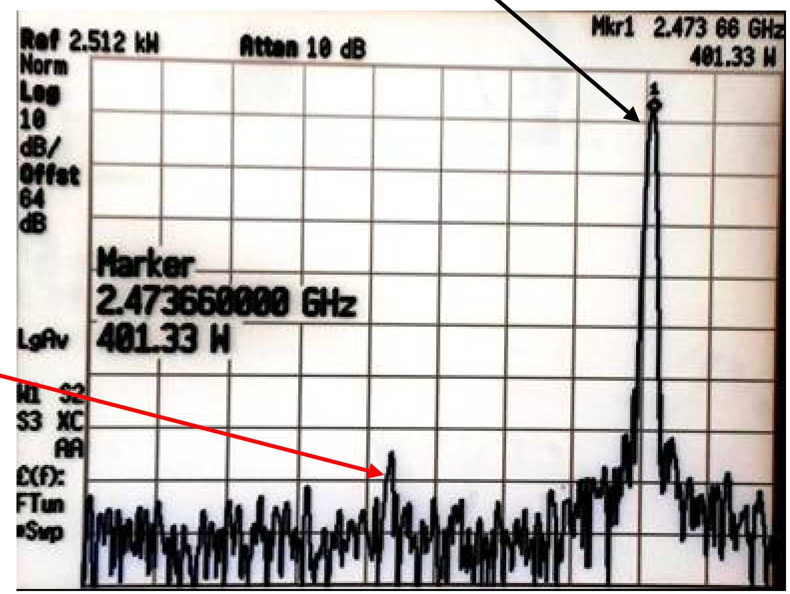
Peak of free running magnetron-I

RF leakage of magnetron-II



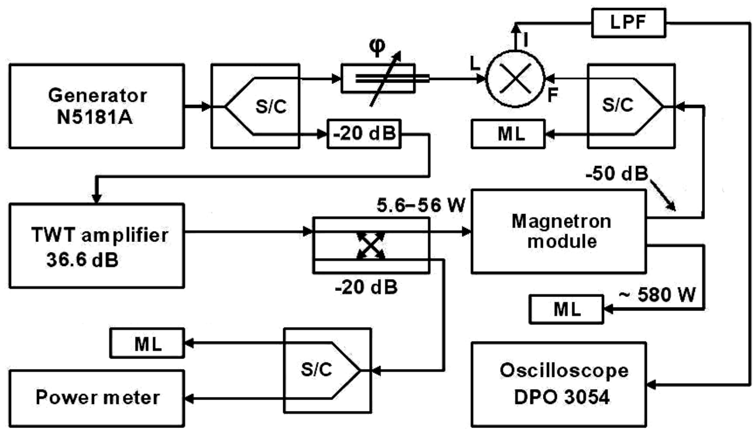
Peak of free running magnetron-II

RF leakage of magnetron-I

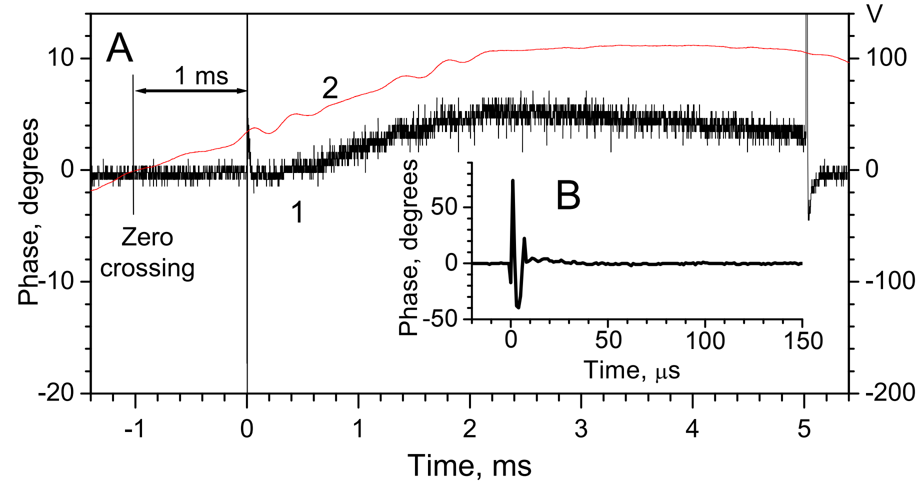


► The magnetrons operated with nominal filament power.

► Verification of operation of the each CW magnetron in injection-locked mode was performed in pulsed regime; each magnetron was pre-excited by CW TWT amplifier, [9].



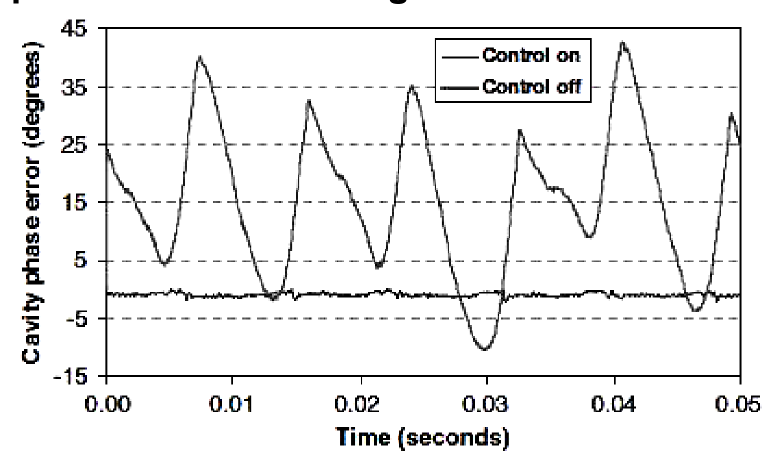
Experimental setup to measure phase variations of the injection-locked magnetron.



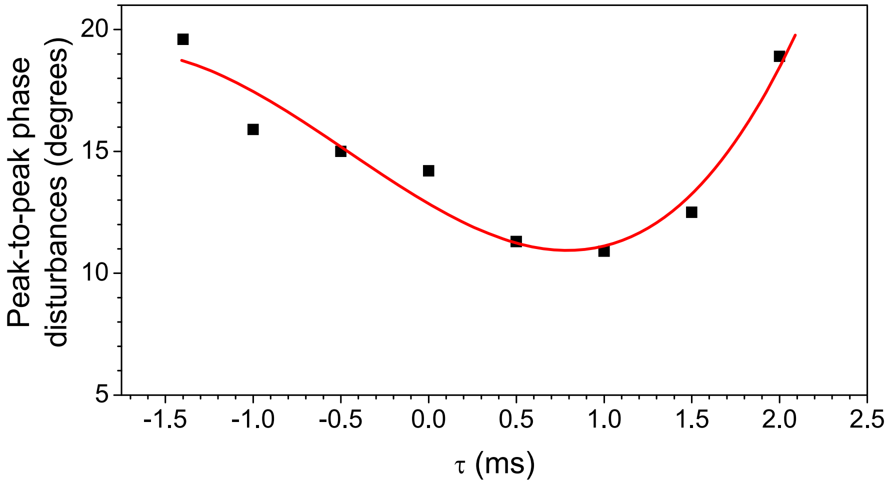
a. Phase variations of the injection-locked magnetron type 2M219J at P_{Out}/P_{Lock} =9.6 dB, trace 1. Trace 2- shape of the AC line voltage. Inset b shows zoomed in time phase variation during first 0.3 ms.

► Measured slow phase variations are regular; they are caused by transient processes in magnetron.

► Measured stochastic phase noise rms magnitude at t ≥50 µs is ≤0.35 degrees.



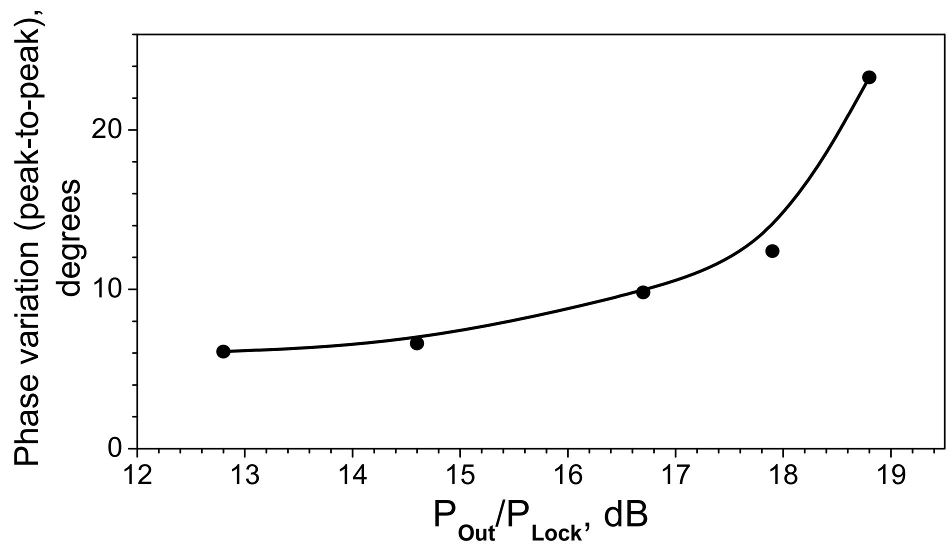
First measured phase instability of voltage in SRF cavity fed by an injection-locked magnetron, [2, 13].



Phase variation of the injection-locked magnetron measured at P_{Out}/P_{Lock} of 15.8 dB vs. the time shift τ.

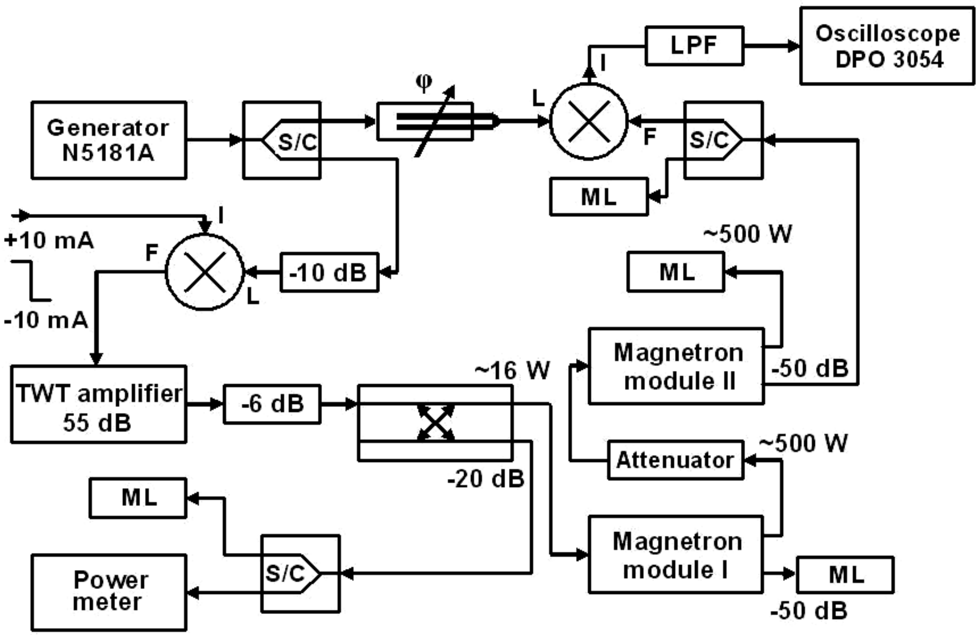
► Measured phase pushing in injection-locked magnetron resulted from current variation is ~ 1.5 deg/1% or ~ 500 deg/A at the ratio of the output power to the locking power of ~ 16 dB.

Dependence of phase variation (peak-to peak) of the injection-locked magnetron on the locking power measured at the output power of 505 ± 5 W.

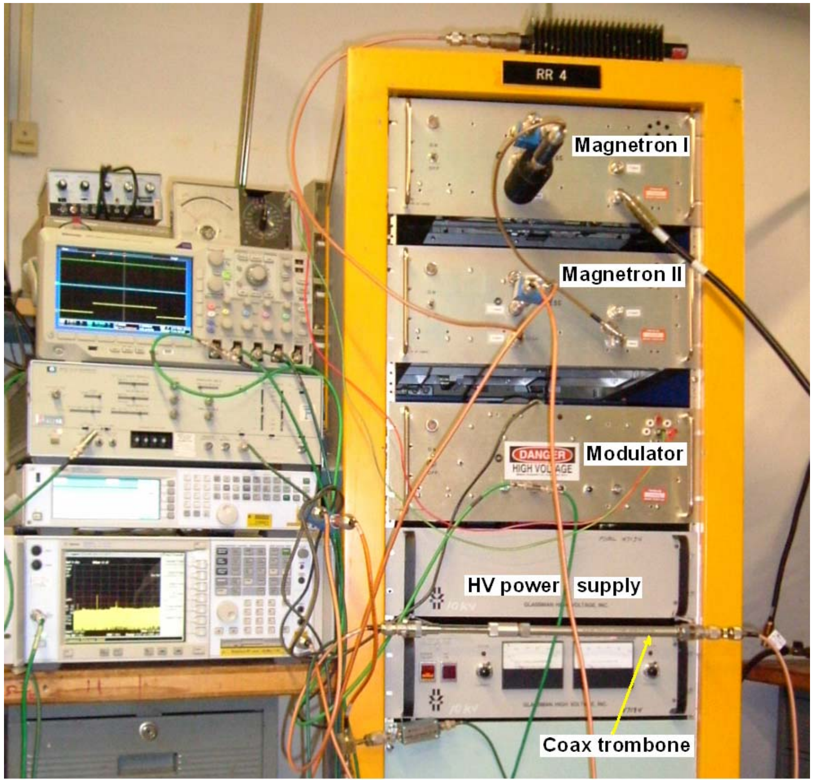


TEST OF CONCEPT OF THE 2-CASCADE MAGNETRON

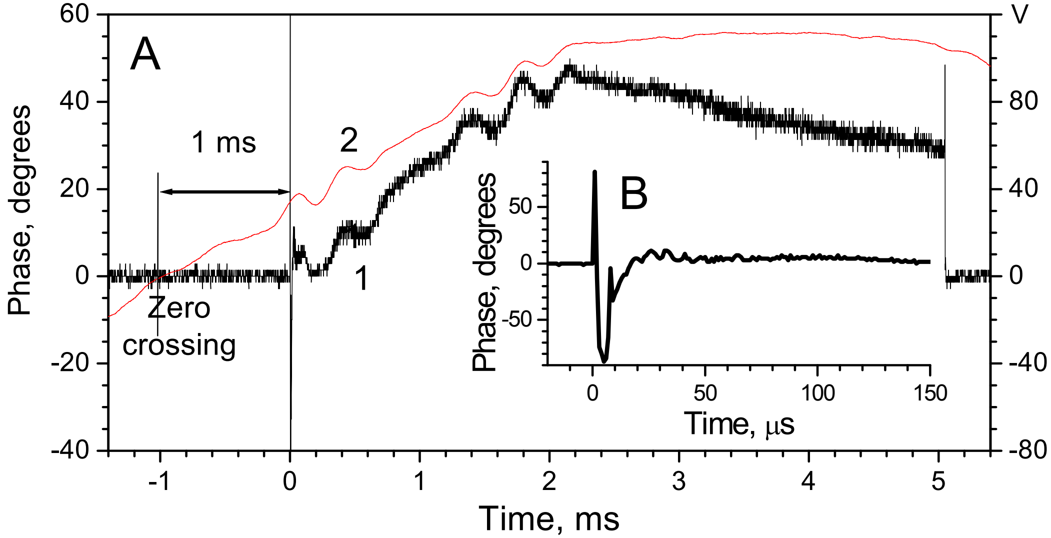
► Operation of the 2-cascade injection-locked magnetron has been verified combining two magnetron modules in series through an attenuator to provide injection-locking in the second magnetron by lowered signal from the first injection-locked magnetron, [14].



Experimental setup to measure phase variation of the 2-cascade injection-locked magnetron



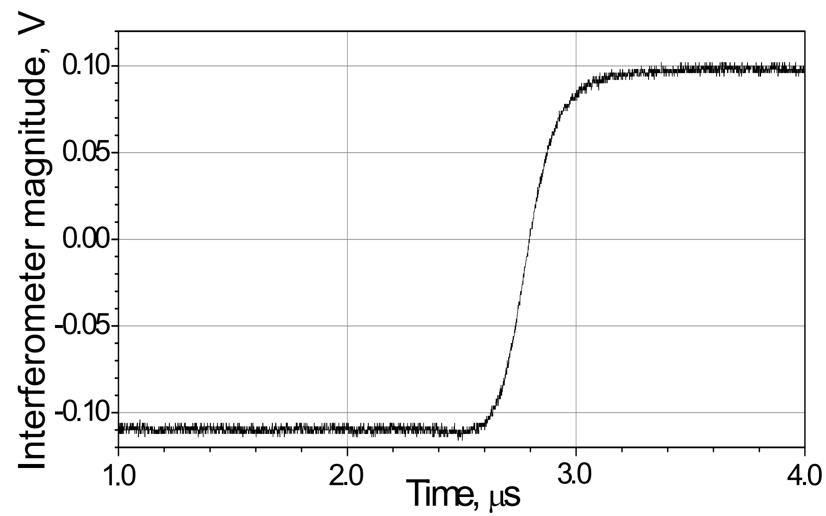
Experimental setup to study 2-cascade injection-locked magnetron



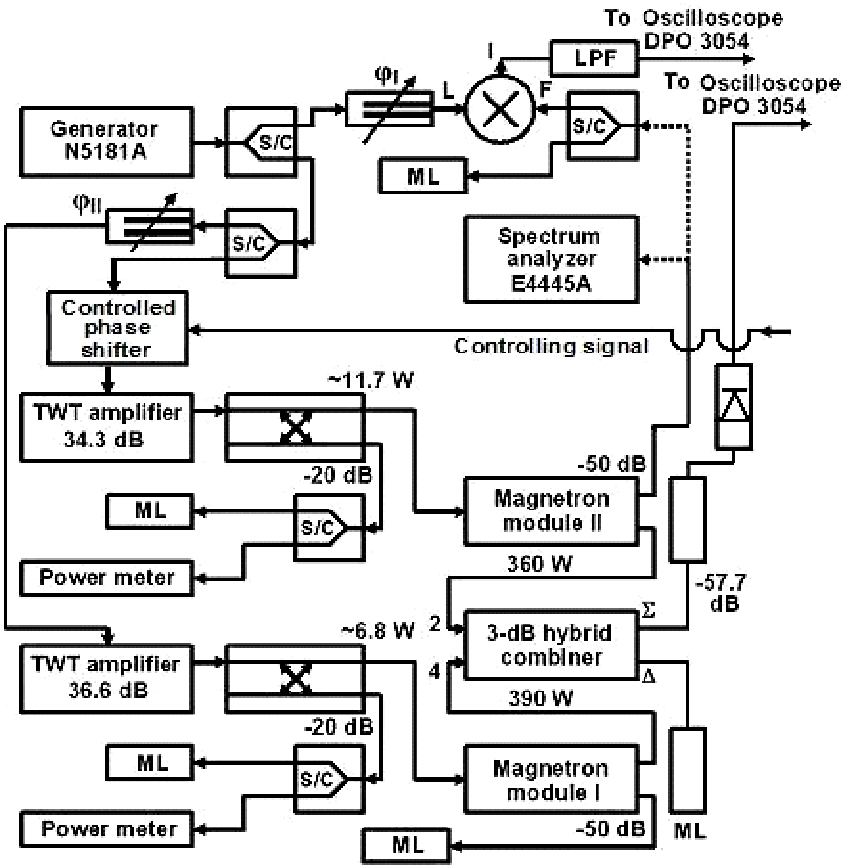
Phase variations of the 2-cascade injection-locked magnetron measured at pulse duration of ≈ 5 ms at the attenuator value of 15 dB, trace 1; shape of the AC line voltage, trace 2. Total value P_{Out}/P_{Lock} is ≈ 30 dB.

► Measured noise rms magnitude at t ≥50 µs is ≤0.7 degrees at the measured ratio of the output power to the locking power of 30 dB and at the output power of ≈500 W.

Response of the frequency-locked 2-cascade magnetron on a fast 180 degrees phase flip measured at ratio of the output power to locking power of 26.5 dB; the interferometer calibration is ~ 0.8 degrees/mV, [14].

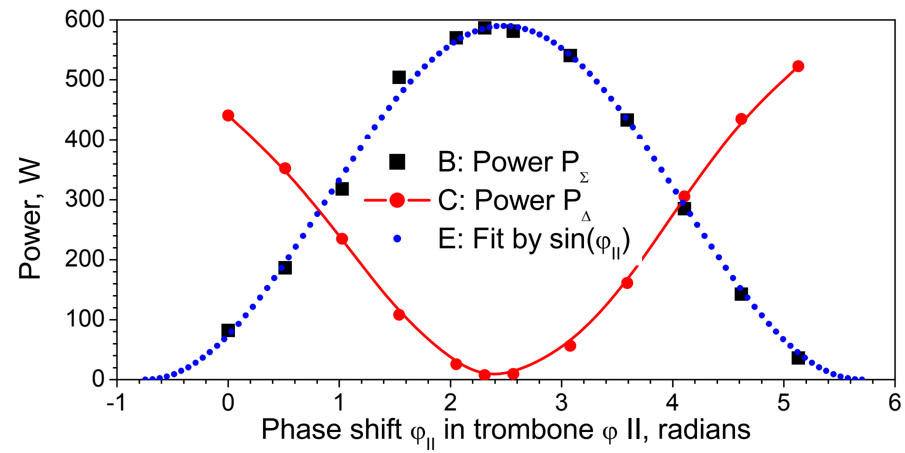


EXPERIMENTAL VERIFICATION OF THE POWER CONTROL CONCEPT IN THE PROPOSED TRANSMITTER

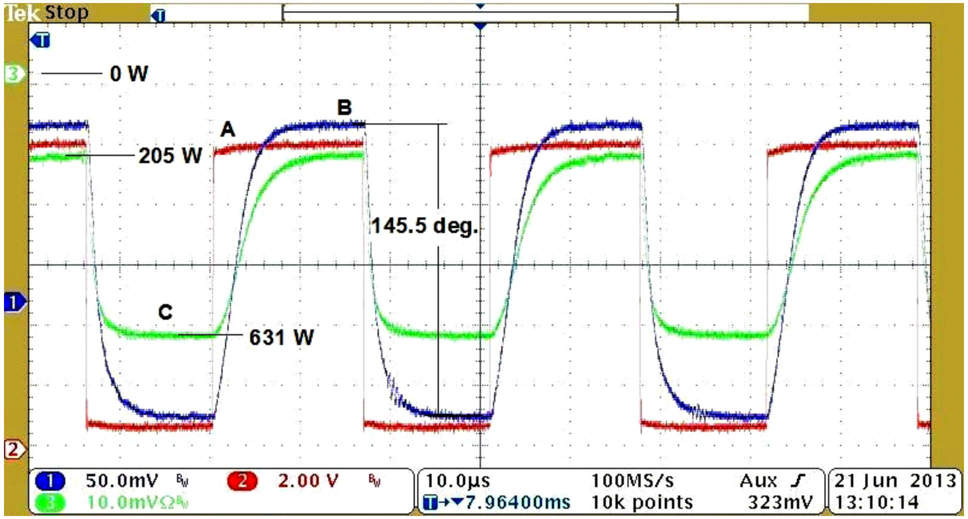


Setup to test the power control concept in static and dynamic modes with the CW, 2.45 GHz, 1 kW injection-locked magnetrons controlled by an analogue phase shifter or trombone φ_{II}

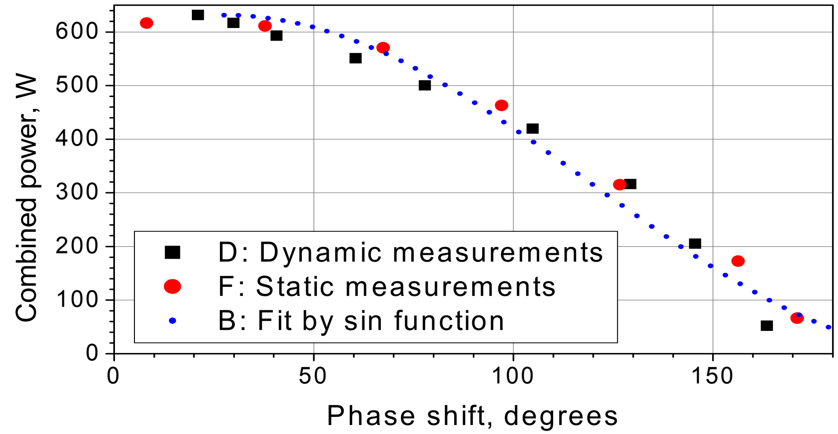
► Measured power levels shown in the setup correspond to ratios of the output power to the locking power of 17.6 dB and 14.9 dB, respectively.



Control of combined power by the phase difference in the injection-locked magnetrons in a static mode.



A- trace of the controlling signal,
B- performance of phase variation by the controlled magnetron,
C- controlled combined power
Modulator pulse duration is ≈15 ms.



Combined power, W, vs. the phase shift

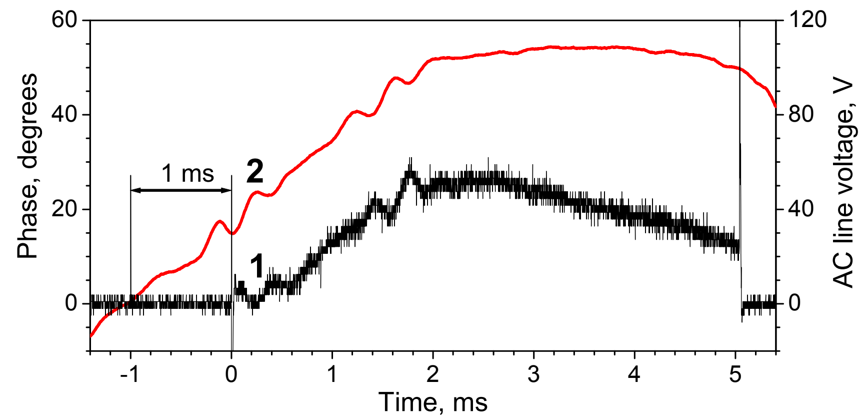
The CW, 1 kW injection-locked magnetrons demonstrate at the phase control the same physical features as the 2.5 MW magnetron locked by frequency (phase)-modulated signal:

► Linearity in the phase response,

► Low phase errors,

► Quite wide bandwidth of control.

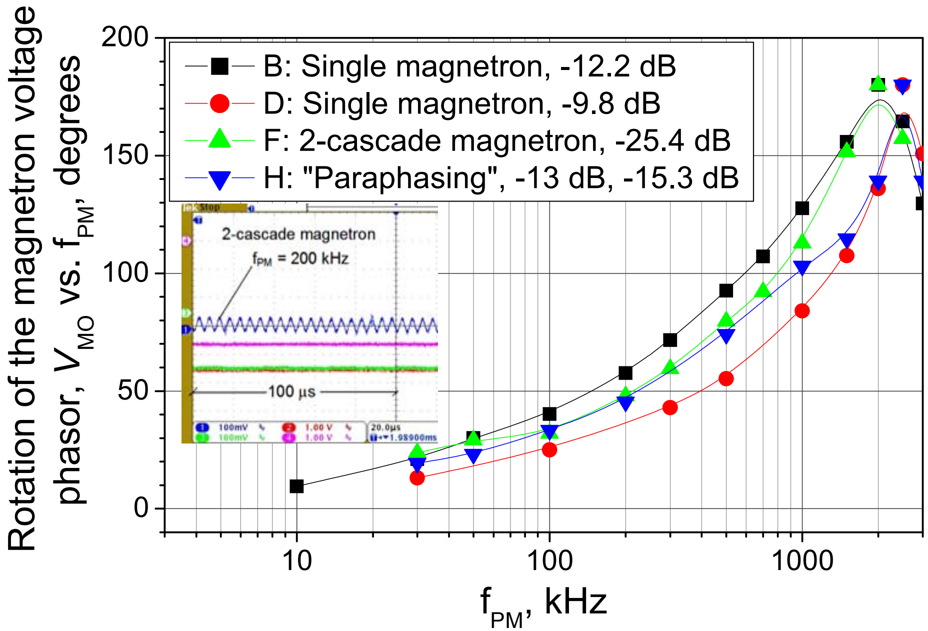
► Trace at t≥ 50 µs measured with the phase detector, has a smooth shape with phase noise rms magnitude of ≤ 0.5 deg.



1- the phase detector trace at the output "Σ" of the hybrid, 2- shape of the AC line voltage.

RAPID CONTROL OF THE MAGNETRONS LOCKED BY A PHASE-MODULATED SIGNAL

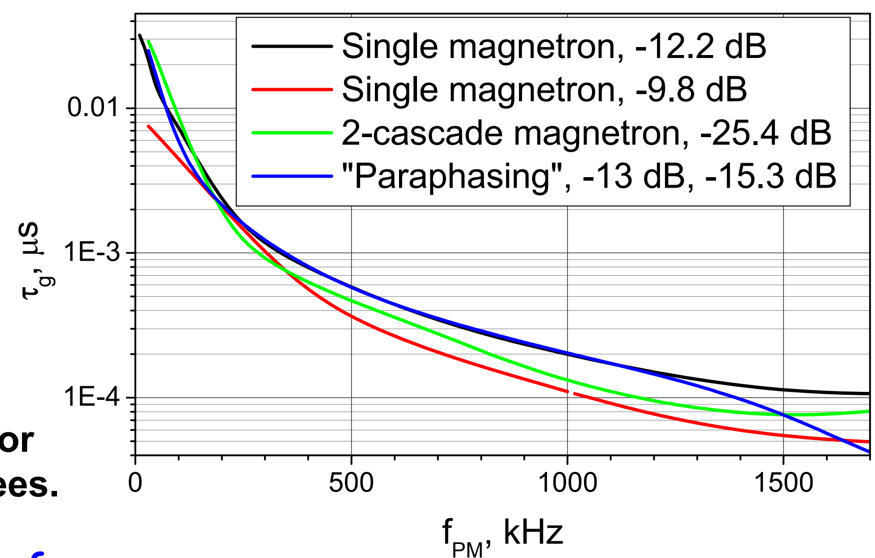
Study of phase response of the injection-locked magnetron at a fast control by the phase-modulated locking signal was performed in all setups at various modulating frequencies and power of the locking signal.



Measured rotation of magnetrons output voltage phasor vs. f_{PM}; magnitude of the phase modulation is 20 degrees.

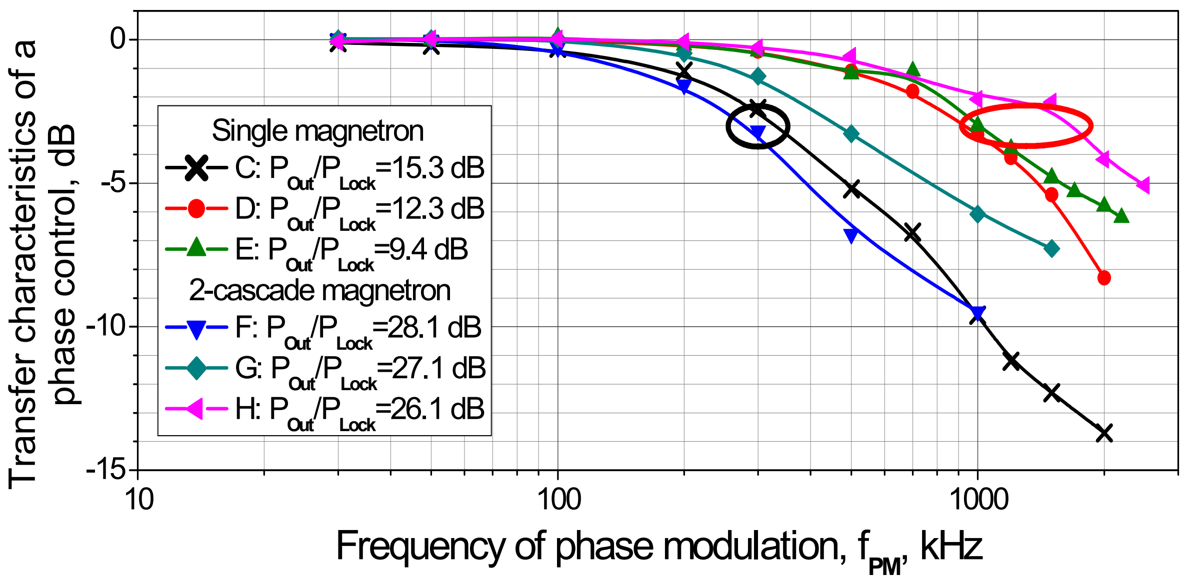
Measured phase delay module, $|\tau_P|=\varphi/2\pi f_{PM}$ of the injection-locked magnetrons is ≤2.6 μs.

The group delay, $\tau_g=-d\varphi/d\omega_{PM}$ of the injection-locked magnetrons is ≤40 **ns**; $\omega_{PM}=2\pi f_{PM}$.



Group delay of the magnetrons phase control

► The injection-locked magnetrons phase management bandwidth was determined by measurements of the magnitude transfer characteristics of the phase control of the magnetrons using phase modulation of the locking signal at various P_{Out}/P_{Lock} values.

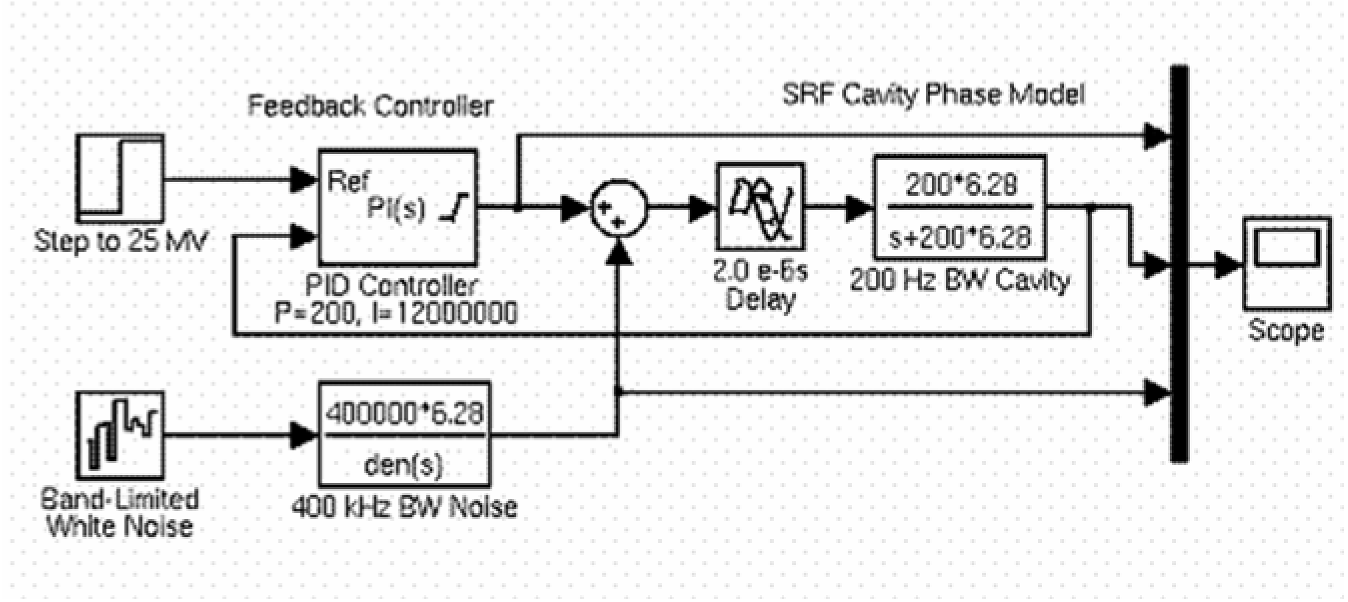


Transfer functions (rms values) of the phase control measured in phase modulation domain .

► The measured transfer characteristics of the phase control in the phase modulation domain implies that a Low Level RF controller may have a closed loop with a bandwidth of ≥100 kHz and will be able to suppress all expected system disturbances like the parasitic frequency/phase modulation with the frequency about of hundreds Hz including phase disturbances from SRF cavity beam loading and the cavity dynamic tuning errors.

► For a phase locking loop with integral gain $I=1.2\cdot10^{7}$ rad./s the parasitic modulation caused by HV power supply ripples at frequency f_r=120 Hz will be suppressed by ≈ $20\log(I/2\pi f_r)$ ≈84 dB.

► Influence of the phase noise of injection-locked magnetrons on the accelerating field in the SRF cavity has been numerically simulated with a simple model of a proportional-integral (PI) feedback phase loop around a superconducting cavity with a broad-band disturbance. The PI loop is setup with a proportional gain of 200 and Integral gain I=1.2·10^7 rad./s.



Simplified model of a LLRF system controlling a superconducting cavity. The loop proportional gain is 200, the integral gain is 1.2·10^7 rad./s, the group delay is 2 μs.

► The performed numerical modelling demonstrate that the broad band noise associated with the greatly exaggerated magnetron noise is suppressed by the controller with the PI loop including the SRF cavity by ≈ 50 dB for peak-to peak measurements.

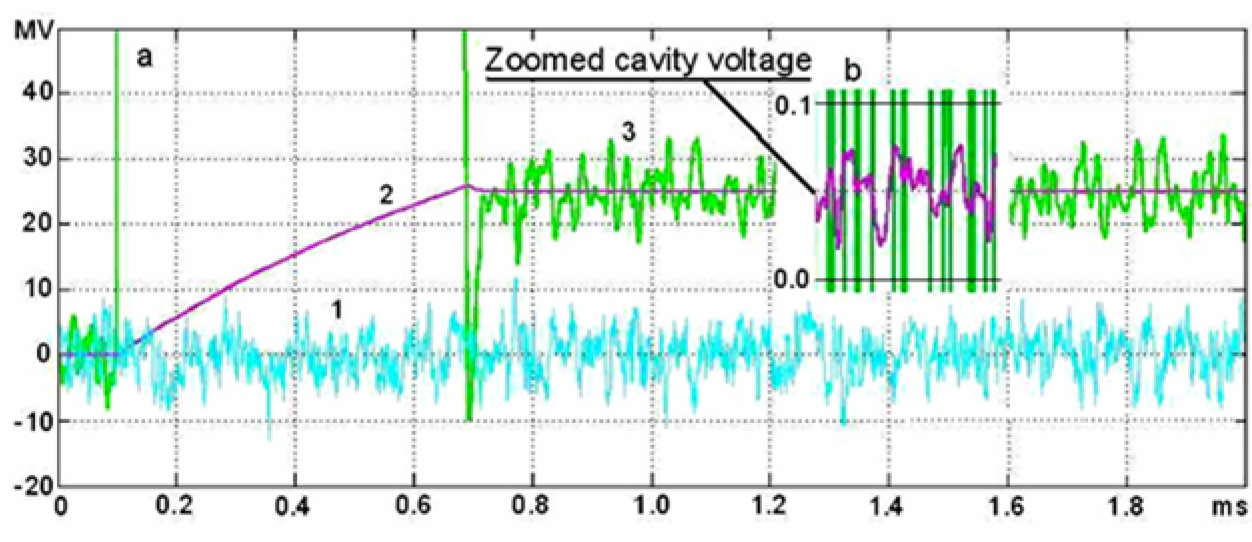


Fig. 23. Traces shown in figure "a" are: curve 1 is the 400 kHz bandwidth disturbance, curve 2 is cavity voltage, curve 3 is RF drive. Vertical scale is 10 MV/division.
The inset "b" presents zoomed in ≈ 300 times (in vertical) trace of the cavity voltage, curve 2, in time domain. Vertical scale in the inset "b" is 0.1 MV/division.

► Since measured fast phase noise magnitude for the injection-locked magnetrons is ≤ 0.8 degrees one expects that the accelerating field amplitude instability caused by the magnetron instantaneous phase noise will be much less than 0.1%.

SUMMARY

► Capabilities of the magnetrons injection-locked by phase-modulated signals were studied using the CW tubes operating in pulsed mode at various setups, modelling all active components of the proposed RF magnetrons-based source.

► What was shown is that injection locking of single and two cascaded magnetrons looks to be feasible, this being a necessary requirement for RF powers exceeding 10 kWatts due to the low "locking gain" of 12-15 dB per magnetron.

► A control a pair of magnetrons in a paraphase mode allowing rapid amplitude and phase management by phase-modulated locking signal has been verified.

► The measured phase modulation bandwidth of over 1.0 MHz appears to be adequate for the accelerator application. The low-frequency phase disturbances less than 45 degrees measured in tests of all active the transmitter components can be suppressed by the phase control system with a wide-band feedback loop.

► High-frequency phase noise of less than 1 degree (rms) measured in the tests of the proposed magnetron source is suitable for the intensity-frontier linacs requirements.

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