POWER CONTROL IN PRE-EXCITED MAGNETRONS

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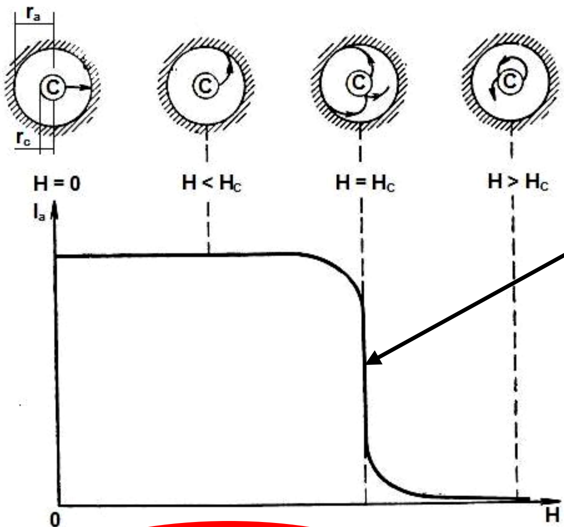
Principle of operation (simplified)

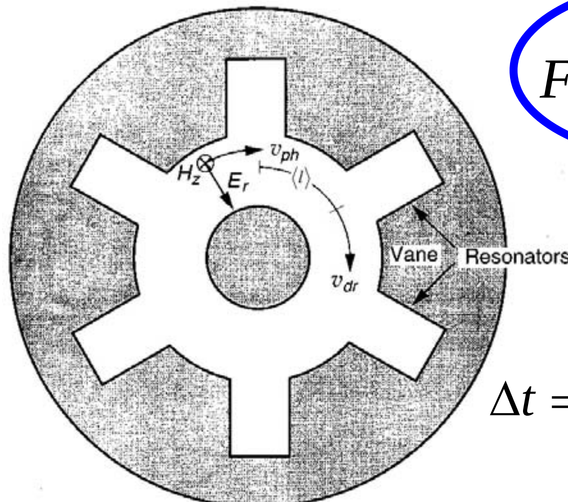


$$\frac{V}{H^2} = \frac{e r_a^2}{8mc^2}\left[1 - \left(\frac{r_c}{r_a}\right)^2\right]^2$$

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

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

$$F_L = F_C$$



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

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

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

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

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

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

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

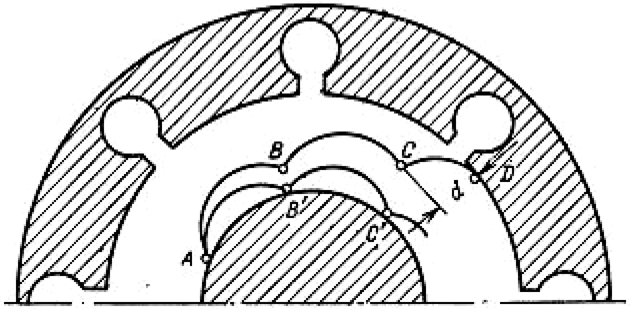
$$U_H = \frac{\pi(r_a^2 - r_c^2)}{n \cdot c} f_n H.$$

U_H-Hartree voltage

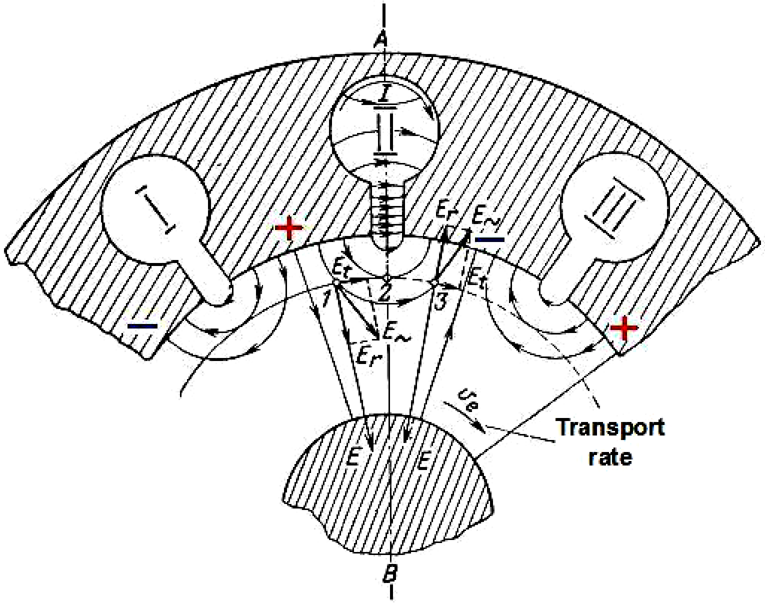
When $U_a \geq U_H$, the Cherenkov synchronism between v_{dr} and $v_{\varphi n}$ is fulfilled.

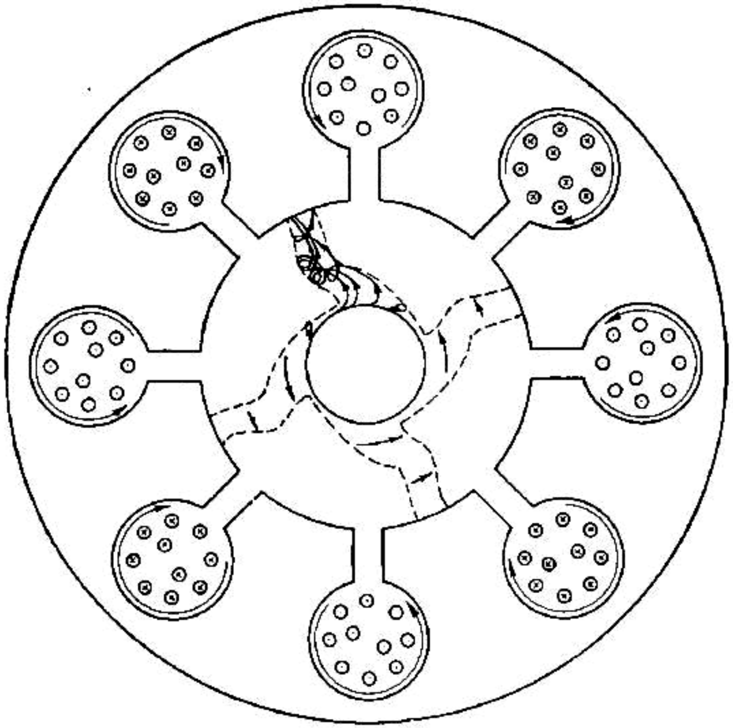
Trajectories and phase focusing in magnetrons

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





Motion of charge in a magnetron at $H > H_c$.

At a plane geometry of a plane magnetron (planotron) the motion of electrons may be described as: $$\ddot{z} + i\Omega\dot{z} = f(z, z^*, t),$$

The equation has an exact solution if ***f(z, z*, t) = Cz***:

$z_0 = \alpha \exp(-i\Omega_1 t) + \beta \exp(-i\Omega_2 t)$, where: $\Omega_2 = \omega_C = (eH)/(m_e c)$, β is radius of the rotating electron, Ω_1 is azimuthal velocity of center of electron orbit, α is radius of rotation of the center of electron he orbit. Motion of center of electron orbit represents motion of charge.

The static electric field, **E**, between coaxial cathode and anode is determined by the applied voltage, **U**, as: $E(r) = U/r \ln(\dot{r}_2/r_1)$. Complex acceleration caused by this field is:

$$f(z, z^*, t) = \frac{e}{m}\frac{U}{\ln(r_2/r_1)\cdot z^*}$$

The drift velocity depends on the radius: $v(r) = \bar{v}\cdot(\bar{r}/r)$,

In a synchronous wave ($\exp(-i(n\varphi + \omega t))$, $\omega = n\Omega_1$) , pre-exciting the magnetron:

$$u(r) = \bar{u}\cdot(r/\bar{r})$$

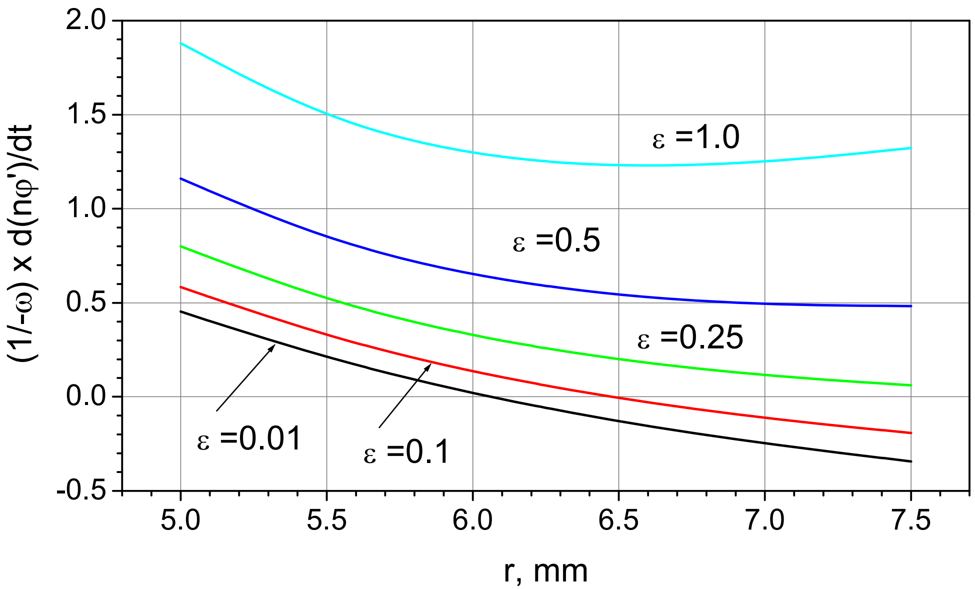
Thus synchronism can be fulfilled only for charge at $r = \bar{r}$.

Motion equations for charge in origin of synchronous wave

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

Phase focusing

Phase defocusing



Function $n\dot{\varphi}'/(-\omega)$ **vs. the radius of the charge trajectory, r, at r_c =5 mm, r_a/r_c =1.5,** $\bar{r}/r_c$ **=1.2, nφ'=π/2**

Equations for charge motion in origin of the rotating synchronous wave at:

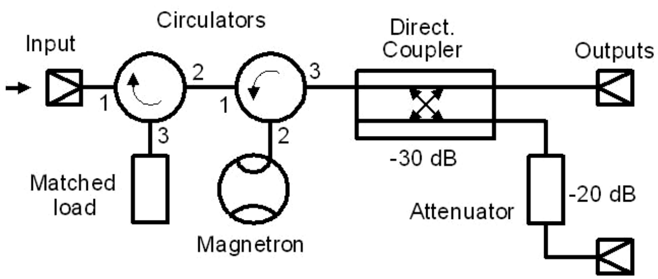
$$\varphi' = \varphi + \omega \cdot t/n,$$

$$\varepsilon = \tilde{E}_c / E_c = \tilde{E}_c \cdot r_c \ln(r_a / r_c)/U,$$

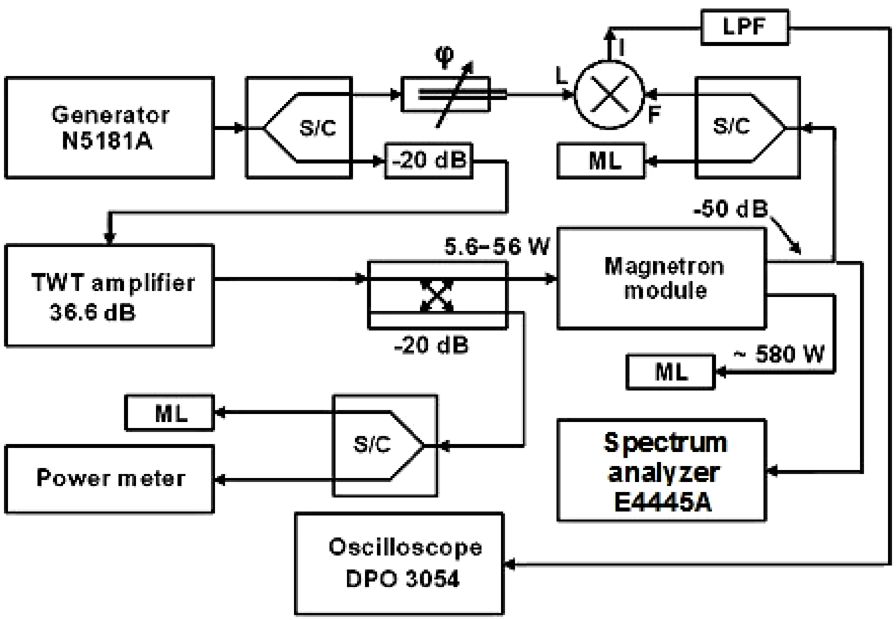
Potential Φ_1 represents RF field, potential Φ_0 represents static electric field in the rotating origin.

- **Motion of charge towards anode is possible in the interval (–π/2< nφ'<π/2)**
- **At small ε in points of "rest", where d(nφ')/dt=0, the phase focusing of charge into "spokes" is impossible. These points don't allow motion of charge towards anode.**
- **An increase of ε eliminates the points of "rest", this allows phase focusing and drift of charge towards anode, i.e. the magnetron current.**

Experimental tests: lowering of magnetron start up voltage

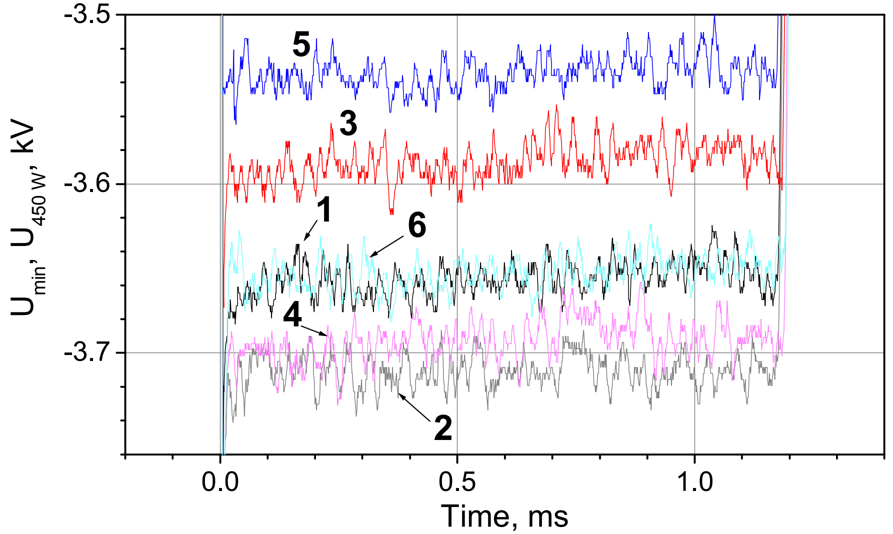


The magnetron assembly to study the power control.



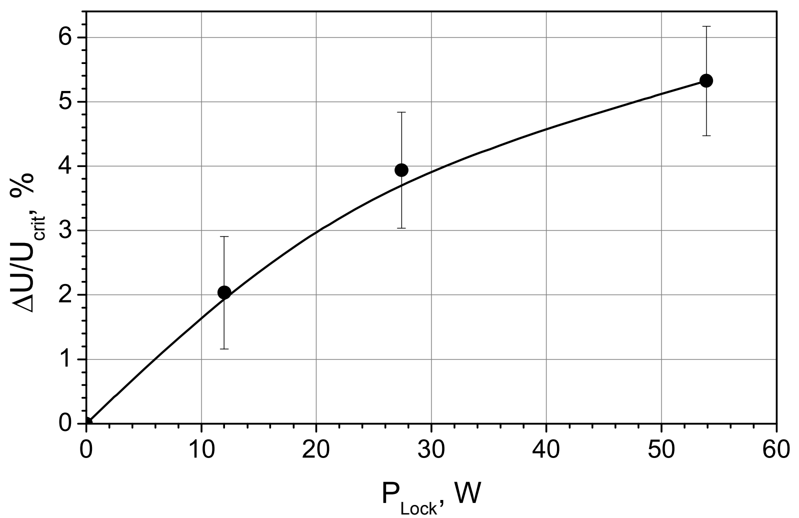
Experimental setup to measure the magnetron current, voltage, spectrum, output power, power of the pre-exciting (frequency-locking) signal and phase noise.

The measurements in pulsed mode were performed at 2.7 MHz shift of the frequency locking the magnetron.

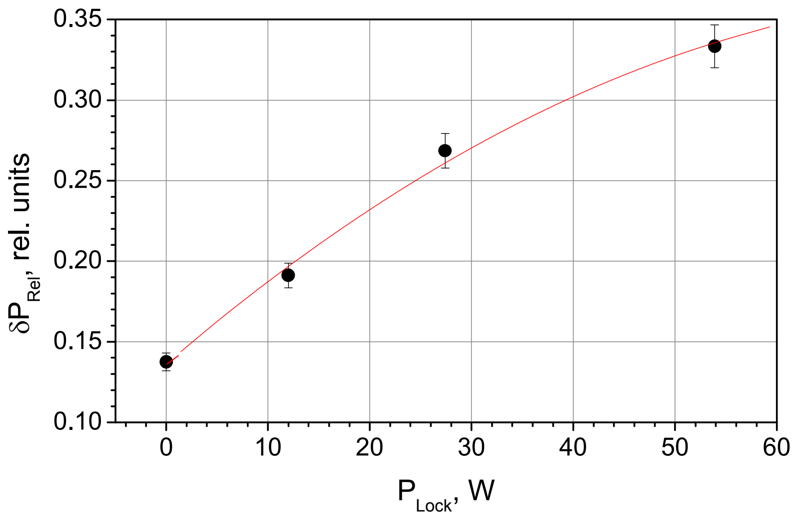


Pulsed cathode voltage at minimum generated power, traces 1, 3, 5, and at power of 450 ±8 W, traces 2, 4, 6 at the following powers of the frequency-locking signal, P_{Lock}: 12 W, traces 1 and 2, 27.4 W, traces 3 and 4, 53.9 W, traces 5 and 6, respectively.
Minimum amplitude of the free running magnetron is 3,737±9 V

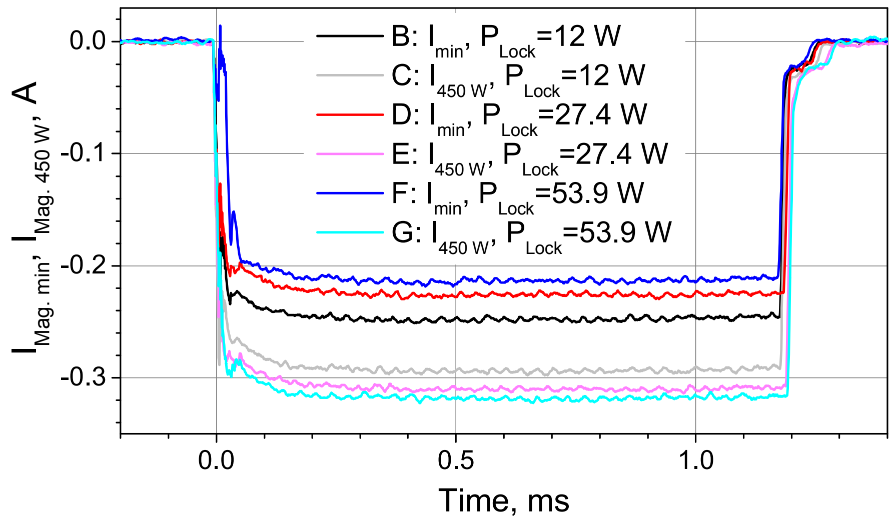
Lowering of magnetron start up voltage and current



Lowering of magnetron start up voltage in percents vs. the power of signal, P_{Lock}, pre-exciting the magnetron.

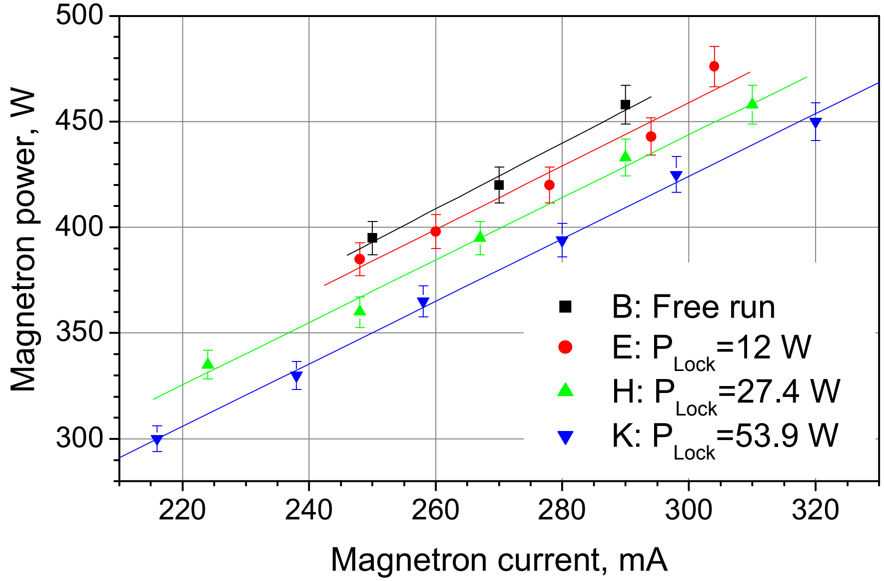


Measured allowable range of the power control of the magnetron vs. the pre-exciting power.

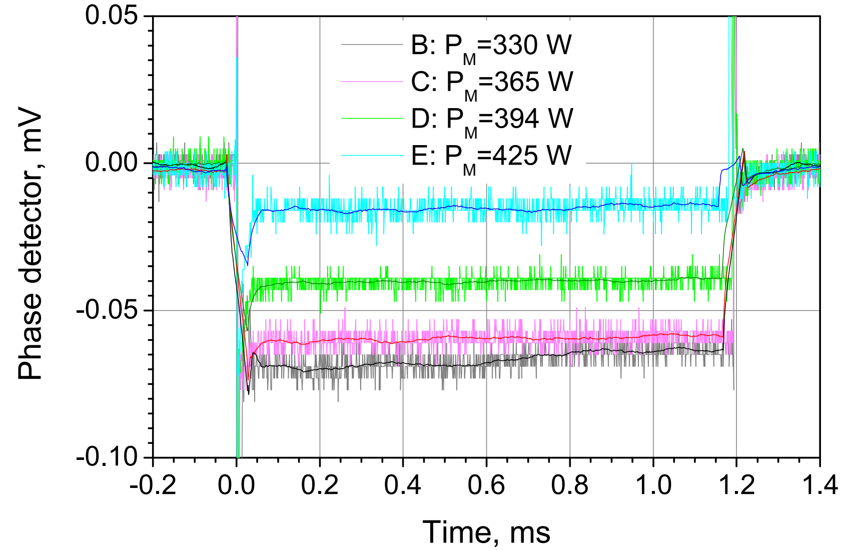


Traces of the measured pulsed cathode current at minimum generated power and at power of 450 ±8 W at various power of the frequency-locking signal, P_{Lock}.

Magnetron power control by control of the current



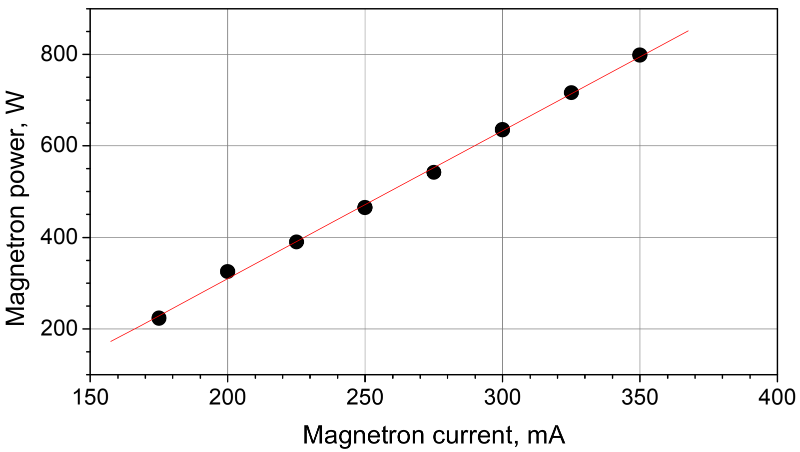
Dots with error bars: dependence of the magnetron pulsed power on the magnetron current vs. power of pre-exciting signal. Solid lines: linear fits of the measured data.



Measured by the phase detector stochastic noise at various magnetron power. Calibration is 2.4 mV/degree.

P_{Mag}, W	300	330	365	394	425	450
P_{Lock}, W	52.9	54	54.1	54.1	54.1	54.1
Phase noise, deg. (rms)	1.4	1.3	1.4	1.0	1.3	1.0

Experimental tests in CW mode



The measurements in CW mode were performed at the frequency locking the magnetron approximately equal to average frequency at free run at magnetron power of ~800 W.

Power of the frequency-locked 1.2 kW CW magnetron vs. the magnetron current at the locking power of ≈50 W.