OTHER RF POWER SOURCES

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The main subjects discussed in this paper are as follows. Triode tube; main characteristics of the equivalent schematic of the amplifying stage. Requirements for operation of a triode stage loaded with an accelerating cavity. Influence of parameters of the output stage and transmission line length on the output impedance of RF system for the beam. Typical design of the power output stage. Magnetron, travelling-wave tube, principles of operation, main parameters. Magnetron loaded with a microtron cavity, methods of coupling, requirements for stable operation. Magnicon - BHF generator with a circular deflection of the electron beam, principle of operation, results of development.

1 Triode tube

Klystrons have wide acceptance as an RF power source, but at frequencies lower than 300 MHz they are not used. Therefore frequencies below 300 MHz are in the domain of grid tubes - triodes and tetrodes. An RF system with lower frequency has some advantages: reduced interaction with material structures (elements of the vacuum chamber and cavity) because of larger bunch length, the possibility of having a high peak current in one bunch and effective injection because of a larger energy bucket.

The triode tube has an anode and a heated cathode (Fig.1). Electrons are emitted from the cathode and collected at the anode. The energy of the electrons is a function of the voltage between the anode and the cathode. The grid is usually a helix made of wire wound around the cathode. Since the grid is installed between cathode and anode, its influence on the electric field near the cathode is stronger. The voltage between grid and cathode determines the number of electrons collected at the anode, i.e. the electric current between the electrodes. Variation of anode potential also influences the current, but by much less. Negative voltage between grid and cathode holds up electrons coming out of the cathode surface; the space charge is increasing and the number of electrons going through the grid is decreasing.

If a positive voltage is applied between grid and cathode, some electrons get to the grid causing a grid current. A larger portion of the electrons go to the anode, so the cathode current I_k divides into two components, forming the anode current I_a and the grid current I_g :

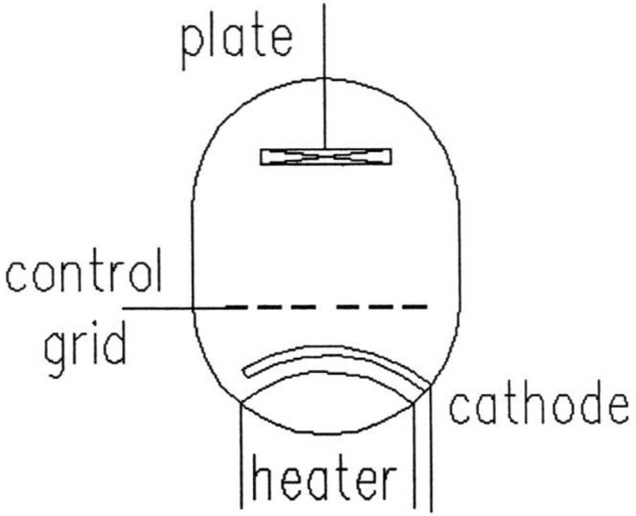


Figure 1: Triode tube.

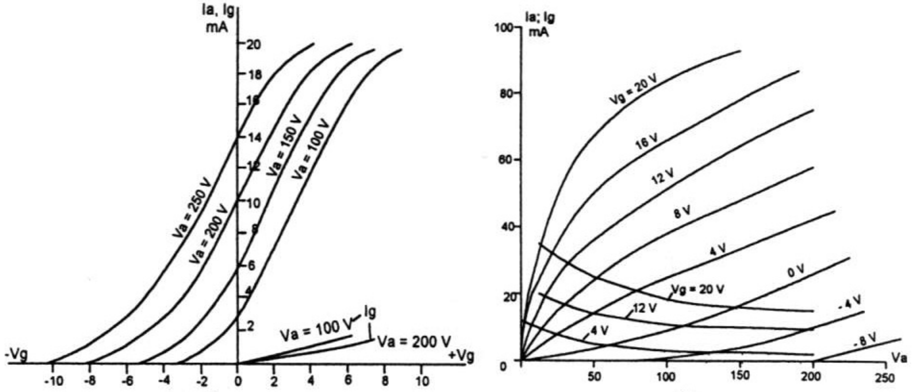
$$I_k = I_g + I_a . \tag{1}$$

These current values depend on anode voltage V_a and grid voltage V_g, and the triode behaviour can be described by 4 functions:

$$I_a = f(V_g) \qquad V_a = const, \tag{2}$$
$$I_a = f'(V_a) \qquad V_g = const, \tag{3}$$
$$I_g = \varphi(V_g) \qquad V_a = const, \tag{4}$$
$$I_g = \varphi'(V_a) \qquad V_g = const. \tag{5}$$

All these functions are usually obtained by direct measurement. For example, in order to get characteristic curve (2) one varies grid voltage and measures anode current with the anode voltage kept constant. These functions are called static characteristic curves. The typical triode characteristics (2) and (4) are shown in Fig. 2a and characteristics (3) and (5) in Fig. 2b.

Both families of characteristic curves may show some variation depending on the specific design or the area of application of the tubes, but the same tendencies are seen in the curves for any type of triode. Since either of the two families is a graphic representation of Eqs. (2) to (5), they are interdependant.



a) b)

Figure 2: Two families of anode-grid characteristic curves.

One can transform the family of Fig. 2a into that of Fig. 2b by using another coordinate system.

These two sets of characteristics provide complete information about a tube's parameters within the range shown. For quick estimation of the suitability of a tube for a specific application, to compare two tubes, the static characteristics are often used. For example, Fig. 2 shows the dependence of the anode current on the grid voltage is not uniform throughout the range of anode voltage. Usually static characteristics show the behaviour of the tube in the most usable range of parameters or at some given operational point.

One of the most important characteristics is the transconductance S. It shows the change in anode current per volt of grid voltage change:

$$S = \frac{dI_a}{dV_g} \quad \text{for} \quad V_a = \text{const.} \tag{6}$$

Often the anode current is measured in mA, then the dimension for the transconductance is mA/V. Transconductance is affected strongly by anode and grid voltage, but only one value is given in the tube data sheet: the average value for the rising and sufficiently large and linear part of the anode and grid curve, the part used as operational for amplifiers and generators. The transconductance of power triode tubes is in the range 10 to 150 mA/V.

The second important characteristic is the anode resistance,

$$R_i = \frac{dV_a}{dI_a} \quad \text{for} \quad V_g = \text{const.} \tag{7}$$

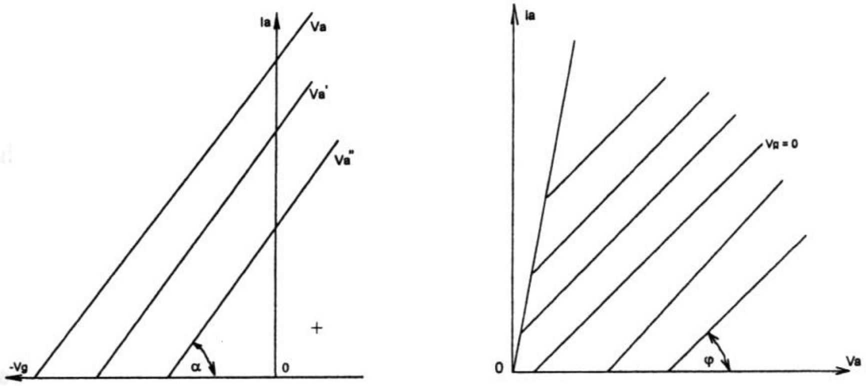
The anode resistance determines the penetration of electric field from anode through grid and the influence of the field on cathode current. R_i is the output resistance of the tube for ac.

The amplification factor is

$$\mu = -\frac{dV_a}{dV_g} \quad \text{for} \quad I_a = \text{const.} \tag{8}$$

A characteristic μ shows the relative influence of anode and grid potentials on the anode current. The value of μ is dimentionless and is in the range 10 to 100.

Usually for practical calculations the curves in Fig. 2a,b are approximated by lines (Fig. 3 a, b):



a) b)

Figure 3: Approximation of anode-grid characteristic curves.

$$\tan\alpha = S = \frac{\Delta I_a}{\Delta V_g}\,; \quad \tan\varphi = \frac{1}{R_i} = \frac{\Delta I_a}{\Delta V_a}. \tag{9}$$

$$\text{for } V_a = \text{const} \qquad \text{for } V_g = \text{const}$$

The error of approximation is not large and is compensated by simplicity of calculation.

The parasitic capacitances between the tube's electrodes have to be taken into account when designing at RF. At frequencies of several MHz and higher, part of the output power would come through the capacitances back to the stage input. The result could be distortion of the frequency response and even oscillation of the stage.

Figure 4 shows capacitance from cathode to anode (C_{ka}), from grid to anode (C_{ga}), and from cathode to grid (C_{kg}).

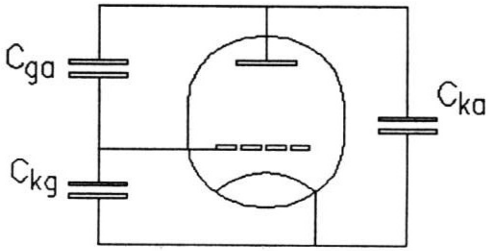


Figure 4: Capacitances of triode.

At lower frequency the common cathode configuration is often used. The equivalent schematic of the stage is shown in Fig. 5.

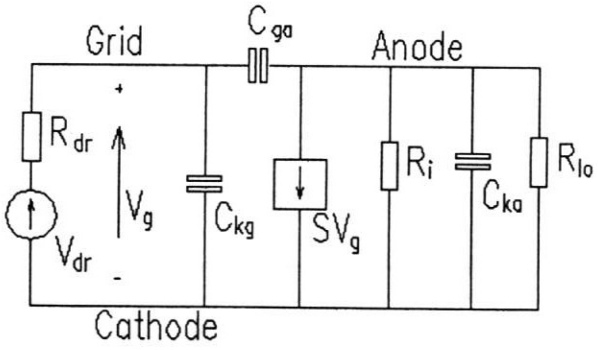


Figure 5: Equivalent circuit of a common cathode stage R_{dr} - output impedance of the driver stage, V_{dr} - driver voltage., R_{lo} - load impedance.

1.1 RF Common Grid Power Stage

Usually on power stages of RF generators the triode is in the grounded grid configuration. This offers larger power gain because of smaller feedback through the parasitic capacitance C_{ka}:

$$C_{ka} << C_{ga}. \tag{10}$$

If the frequency band in not large, the resonance circuits are used as anode load. An example of the power triode stage coupled with the cavity through the transmission line is shown in Fig. 6.

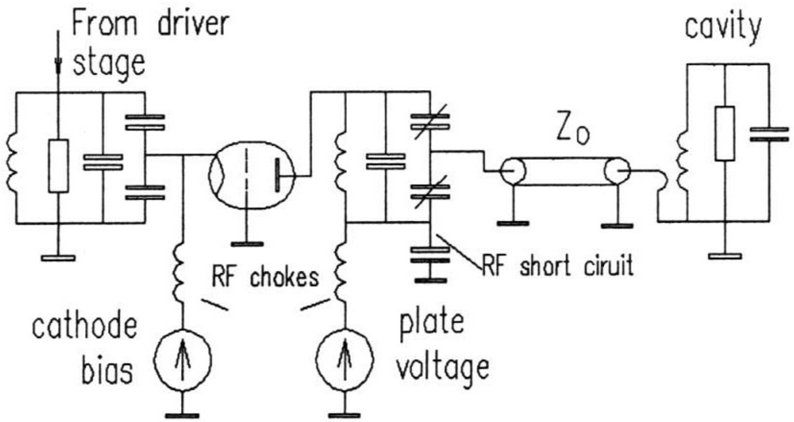


Figure 6: Schematic of the common grid power stage.

The equivalent circuit of the stage is shown in Fig. 7. For higher efficiency the conductance angle of the tube may be 180°or less; therefore the effective S and R_i should be calculated and used. The anode cavity is tuned so that the ratio V_{aa}/I_a is maximum:

$$V_{aa} = -\frac{I_a(S+Y_c+G_i)}{Y_a(Y_k+S+Y_c+G_i)+Y_k(Y_c+G_i)}\,. \tag{11}$$

If the denominator of Eq. (11) is 0, the stage will lose its stability. This may be used as the condition for the stage oscillation. To increase the stage stability, additional resistive loading of anode and/or cathode circuits is used.

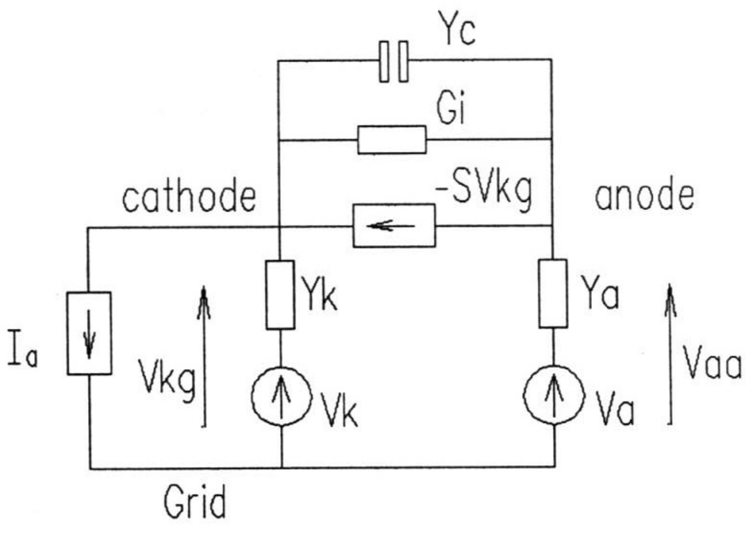


Figure 7: Equivalent circuit of common grid stage. Y_k - conductance of driver stage; Y_a - conductance of anode cavity together with external load; $Y_c = 1/j\omega C_{ka}$; G_i - effective anode conductance; S - effective tube transconductance; V_k - DC cathode bias; V_a - DC anode power supply; I_a- equivalent driver current.

1.2 Equivalent Circuit of the Output Stage

For matching the equivalent anode load with the impedance of the transmission line, and the impedance of the transmission line with that of the cavity coupler, transformers of various kinds are used.

The transformer can be represented by a reactive quadrupole (Fig. 8a). The section "a" is a reference plane of the accelerating cavity or generator output stage, and "b" is connected to a transmission line.

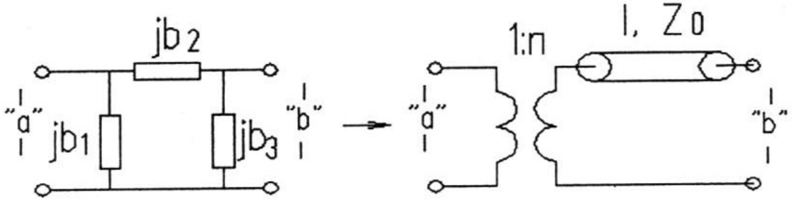
It is convenient to replace the reactive quadrupole with some uniform network, i.e. an ideal transformer and a piece of transmission line (Fig. 8b). The replacement is possible if one of the elements of the reactive quadrupole is dependent on others. It is convenient if the dependant element is b_1, because then its change can be compensated for by corresponding tuning of the anode or accelerating cavity connected to section "a." The length of transmission line piece l and the transformation factor n are determined by b_2 and b_3, which are normalised to the line impedance:

$$\sin\frac{2\pi l}{\lambda} = -\frac{b_2/|b_2|}{\sqrt{1+(b_2+b_3)^2}}\,, \tag{12}$$

$$n^2 = \frac{b_2^2}{1+(b_2+b_3)^2}\,. \tag{13}$$

The value of b_l is equal to

$$b_1 = b_2\left(b_2\cdot\frac{b_2+b_3}{1+(b_2+b_3)^2} - 1\right). \tag{14}$$



a) b)

Figure 8: Equivalent representation of reactive quadrupole.

These equations show that the coupling of the cavity with the output stage can be adjusted by variation of 3 parameters:

a) n_1 - the transformation factor from anode to transmission line,
b) n_2 - the transformation factor from cavity to transmission line,
c) L_e - the equivalent length of transmission line.

The parameters of the whole network will not be changed if both transformers are excluded and the parameters of the anode and accelerating cavity are replaced with ones that are normalised to the transmission line. Section "a_g" and "a_c" (Fig. 9) are the reference planes of the generator and cavity respectively, and L_e is the equivalent length of transmission line between sections.

This representation provides a simple model that describes the interaction of beam with the RF system.

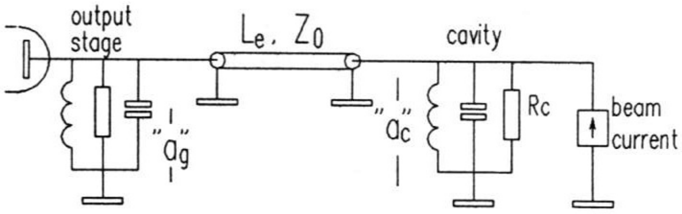


Figure 9: Equivalent circuit of the output stage, transmission line, and accelerating cavity.

1.3 Requirements for RF power generator

1. The output power of the RF generator should be sufficient to compensate for resistive losses in the cavity walls at the designated accelerating gap voltage.

2. The generator delivers RF power to the cavity, which is transferred through the electric field to the charged particles to accelerate them or to compensate their energy losses due to synchrotron radiation and other causes.

3. The reactive beam current through the cavity can be compensated for by corresponding tuning of the cavity, but it changes quickly after injection. In order to maintain the designated gap voltage until the tuner reacts, this reactive current must be compensated for by additional current from the output stage. In some machines this additional current may be as large as the stationary one or even larger. Therefore the output tube should have reserves of anode current and anode dissipation power.

4. The output impedance of the RF system transferred to the cavity gap must satisfy certain requirements. Since the output stage and the power transmission line are coupled to the cavity, the RF output impedance depends on these elements, and this must be taken into account during RF system design.

5. The amplitude and phase modulations of the RF generator output signal cause phase oscillation of bunches and growth of their length. This growth should be much smaller than the normal bunch length defined by quantum fluctuations of synchrotron radiation.

6. The output stage of the RF generator may be coupled with the cavity through a long transmission line. In that case the impedance of the anode cavity has resonances near the generator frequency. The shunt impedance of those resonances may be much higher than that of a working one. In this situation the stable gain of the output stage will be smaller and special measures have to be taken against oscillation.

1.4 The Tuning Procedure

1. The cavity loaded with a beam is tuned to a resonance.

2. The coupling coefficient of the cavity is fixed so that the cavity is matched with the transmission line under maximum beam load condition.

3. The coupling coefficient of the output stage with the cavity is arranged so that operational parameters of the tube are optimum for maximum power in the transmission line.

4. The anode cavity is tuned to resonance, because the equivalent impedance of anode cavity should be real for optimal operation.

1.5 Methods of RF System Design

Two methods of RF system design are possible.

I. The equivalent length of the transmission line is half wavelength multiplied by an integer:

$$L_e = n \cdot \frac{\lambda}{2} \qquad n = 0,\ 1,\ 2\ \ldots\ . \tag{15}$$

The ratio of cavity gap voltage to anode RF voltage does not depend on beam current and energy for this design. When the cavity load is growing, the driver power is increased by the action of a feedback loop in order to keep the cavity voltage constant. The efficiency of the output stage does not change. This method of coupling provides optimum operational parameters of the output stage when the real conductance of the load varies over wide range. Tuning of the anode cavity and correction of coupling are not required during operation. The RF system needs only one on-line tuner for the accelerating cavity.

The impedance of the RF system for the beam is like that of one resonance LC circuit, formed by summing the anode and accelerating cavity conductances. Therefore, the tuning of the cavity down the frequency for reactive beam current compensation provides for desirable frequency response and results in damping of synchrotron oscillation. If the accelerating cavity is detuned, the output stage is working on short circuit, and all power consumed from the DC anode supply will be dissipated at the anode. Therefore the current in the cavity coupling loop is limited by maximum ratings for anode dissipation.

The drawback of such a design is the possibility of sparking or overload in the transmission line and cavity coupler when tuning of the cavity is wrong.

If the anode cavity is tuned to compensate for the reactive impedance of the accelerating cavity, the voltage and current in the transmission line and coupler may rise beyond maximum allowable values. This disadvantage is corrected in the next approach.

II. The equivalent length of the transmission line is a quarter wavelength multiplied by an odd number:

$$L_e = (2n+1) \cdot \frac{\lambda}{4} \qquad n = 0,\ 1,\ 2\ \dots\ . \tag{16}$$

For this design the ratio of cavity gap voltage to anode current is constant and does not depend on the beam load. An increase of cavity load under constant gap voltage conditions results in an increase of anode ac voltage. The anode current practically does not change. Power dissipation at the anode drops and the efficiency of the output stage grows. Thus the range of load variation is limited by the maximum rating for output tube plate dissipation. The maximum current of the coupling loop of the detuned cavity is equal to that of the matched transmission line under maximum output power conditions. The amplitude of the current is

$$I_a = V_{a\,max}/Z_0 \tag{17}$$

where $V_{a\ max}$ is the ac voltage amplitude at anode reference plane for critical mode of tube operation. For any tuner position of the anode or accelerating cavities, the voltage in the transmission line can not exceed $V_{a\ max}$, and the current in the line and coupler will not exceed $V_{a\ max} / Z_0$. Thus an emergency situation is impossible in this RF system.

1.6 Example of RF triode power stage (Fig. 10)

Triode characteristics:		Capacitances pF:
Amplification factor	$\mu = 40$	$C_{kg} = 170$
Transconductance	$S = 50$ mA/V	$C_{ga} = 47$
Anode resistance	$R_i = 800$ Ohm	$C_{ka} = 2.8$

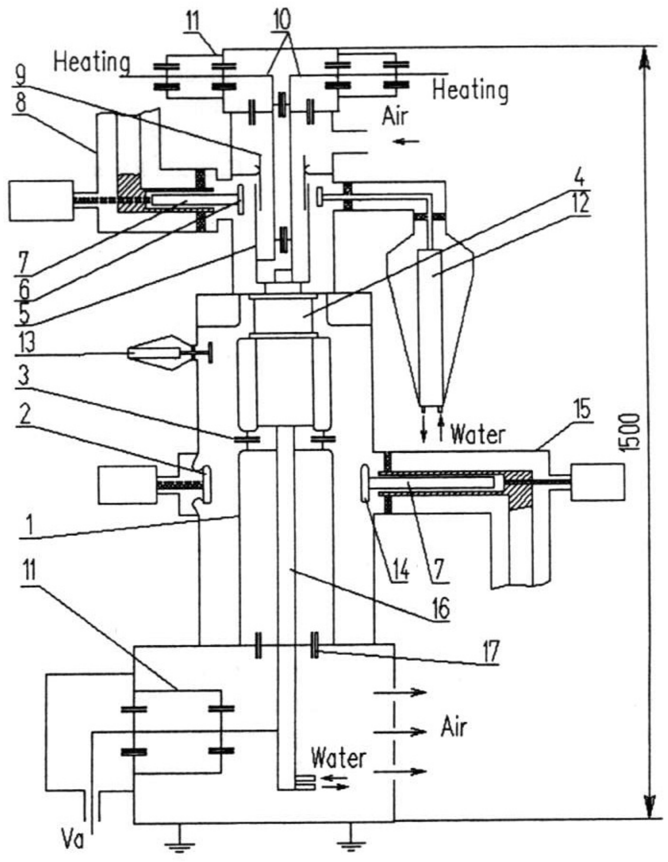


Figure 10: Schematic drawing of RF power stage.

1. Anode cavity
2. Anode cavity tuner
3. Bypass capacitor
4. Triode tube GI-50 (Russia)
5. Cathode cavity.
6. Input coupling capacitor electrode
7. Cylinder capacitance
8. Input transmission line
9. Variable capacitor of cathode cavity tuner
10. RF chokes
11. Low-pass filters
12. Cathode cavity resistive load
13. Resistive load for damping higher-order modes
14. Output coupling capacitance electrode
15. Output transmission line
]16. RF choke
17. Blocking capacitor

Operational parameters (design):

Frequency	181 MHz	Anode DC voltage	5 kV
Input power	6 kW	Cathode DC bias	200 V
Output power	39 kW	Anode RF amplitude	3.6 kV
Anode dissipation	37 kW	Cathode RF amplitude	500 V
Anode current	14 A		

Test results:

Anode DC voltage	5 kV	Output power	45 kW
Cathode DC bias	200 V	Input power	8 kW
Efficiency	50 %		

2 Magnetron

2.1 *Magnetron operation principles*

A magnetron is a cylindrical high-vacuum diode with a cavity resonator system imbedded in the anode. In the presence of suitable crossed electric and magnetic fields the magnetron can be used for generation of continuous-wave and pulsed signal in the higher frequency band. A schematic drawing of the magnetron is shown in Fig. 11.

The magnetic field in the magnetron is applied in parallel to the device axis. The anode DC or pulsed voltage source is connected between anode and cathode, so that magnetic and electric fields are crossed in the interaction zone. The energy available within the zone is coupled out and launched in a coaxial line or waveguide by means of the output probe or antenna.

The magnetron has no separate parts to bunch electrons, a drift space and catcher cavity, as a klystron has. All processes take place in the interaction zone. (See Fig. 12).

The anode DC power supply creates an electric field E_a which, except for a small areas near the cavity slits, is homogeneous. The magnetic field B is perpendicular to the plane of the drawing. The cathode is heated and electrons are emitted from it into the interaction zone.

Suppose that the magnetron does not oscillate and therefore an RF field is zero. The emitted electron will be accelerated by the electric field E_a and start to move to the anode. At the same time a force induced by magnetic field B will start to turn the particle to the right (in Fig. 12). If the magnetic field is strong enough, the electron may not reach the anode, but will be turned back to the cathode. The resulting electric current though the gap will be zero. The curve described by the electron is called a cycloid.

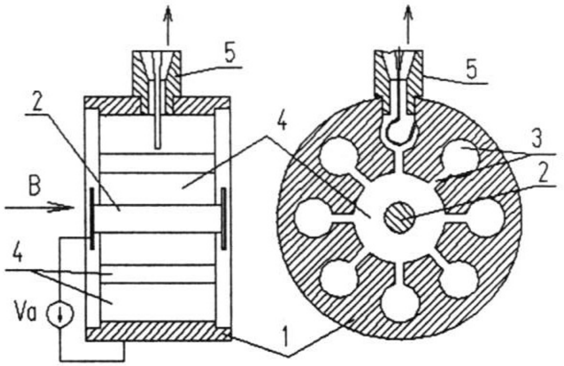


Figure 11: Schematic drawing of magnetron. 1. Anode assembly. 2. Cathode. 3. Cavity of slit-hole type. 4. Interaction zone. 5. RF power output.

If some electron happens to be at position A, it will start to move by the chain of cycloids, arranged in parallel to the cathode (perpendicular to the electric field). Its average speed V_{aver} will be

$$V_{\text{aver}} = \frac{E_a}{B}. \tag{18}$$

The oscillation frequency is a cyclotron frequency ω_c:

$$\omega_c = \frac{eB}{m}, \tag{19}$$

where m is the mass of electron, e is the charge of the electron and the vertical amplitude of oscillation A_v is

$$A_v = \frac{mE_a}{eB^2}. \tag{20}$$

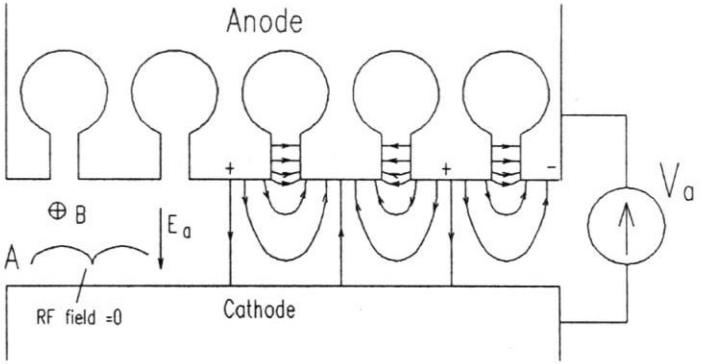


Figure 12: A developed view of magnetron interaction zone.

The cavities embedded in the anode have a strong coupling with each other. The circuit has many resonance frequencies, and each frequency corresponds to a specific mode of oscillation. The number of modes is equal to the number of cavities. There are several strong reasons why only one of the modes is widely used in magnetrons. That mode has a phase shift between neighbouring cavities equal to π and is called the π mode; its electric field is shown in Fig. 12.

Physically, this is a standing-wave oscillation. It is very important that the field have a tangential component of finite magnitude near the cathode surface.

The standing wave can be presented as a sum of 2 waves travelling in opposite directions. The electric field of one, travelling to the right, is shown in Fig. 13.

A magnetron can be designed so that the average speed of an electron is close to the speed of that travelling wave, V_{ph}:

$$V_{\text{ph}} = V_{\text{aver}} . \qquad (21)$$

If an electron is moving in a phase of wave where the electric force is opposite to the direction of electron speed, then for a considerable span of time the electron will transfer its energy to the field's wave.

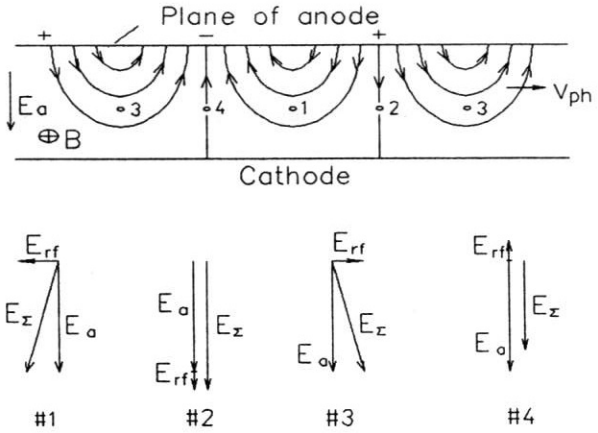


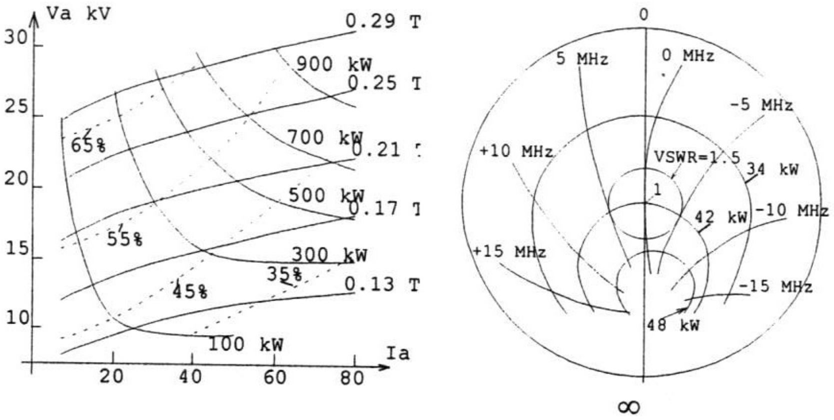
Figure 13: Electric field of the travelling wave in the interaction zone of the magnetron.

That is electron #3 in Fig. 13. The electric field of the wave will be nearly constant for this electron, and the total field that affects the electron's movement can be found as a sum of E_a and the wave field. The corresponding vector diagram for electron #3 is shown in Fig. 13. As mentioned above, the chain of cycloids is arranged perpendicular to the electric field, so the electron will go up the slope, until it hits the anode. The electric current starts to flow through the magnetron. The energy of the hitting electron is much lower than that of the electron accelerated by total V_a in the absence of magnetic field. This difference in energy goes to the electric field of the wave and determines the efficiency of magnetron. Part of this energy is lost in cavity walls, but the major part goes to the magnetron load. For electron #1 the slope will go down, so that the emitted electron will return to the cathode. The direction of the electric field for the particles #2 and #4 will not change, but its value will be different. Therefore, in accordance with the formula (18) for V_{aver} both electrons will approach electron #3 and eventually will go to the anode. This focusing mechanism increases the current of the magnetron and the output power.

In spite of progress in the design of other types of microwave generators, magnetrons still maintain one of the leading positions for efficiency. It is in the range of 60-70% at a wavelength of 10 cm and 20-30% at 1 cm. Maximum output power is in the 10's of MW in pulse mode.

2.2 *Load Characteristics of Magnetron.*

The results of measurement in the magnetron are plotted usually as V_a vs. $f(I_a)$. The parameters for the measurement are magnetic field B, output power P, frequency f, and efficiency η. The typical characteristics are shown in Fig. 14a.



a b

Figure 14: a) Example of load characteristics of the pulse magnetron; b) example of load diagram of the pulse magnetron. λ =3 cm, B = 0.55 T, I_a=10 A. The zero frequency pushing curve corresponds to 9375 MHz.

For a constant magnetic field, the anode current grows rapidly with rising anode voltage and eventually is limited by the emission of the cathode. Thus small variations in applied voltage can cause appreciable changes in operating current.

The constant output power characteristics are like hyperbolas, but the curves are lifted at lower anode voltage and higher current, because of the decrease of the magnetron efficiency.

The load diagram of the magnetron is similar to that of other microwave generators with an output resonance circuit, e.g. a reflex klystron. The data-sheet value of the magnetic field and the anode current are used as fixed parameters for the load diagram. The reference plane for the load diagram is usually the output flange of the tube. A typical load diagram is shown in Fig. 14 b.

One of the important parameters for the magnetron is the pushing of frequency as a result of variation of load. Usually it is given for VSWR=1.5.

2.3 *Magnetrons as RF Power Source for Microtrons*

Magnetrons are often used as RF power sources for microtrons. As a rule, they are pulse tubes with an output power of several megawatts. They are coupled with the microtron cavity through a ferrite isolator or use a dissipative load. Pushing of the magnetron frequency has a stabilizing effect on the whole system. If the magnetron has fixed frequency, the system is adjusted by the cavity tuner. A cavity with fixed frequency can be used with a tunable magnetron. The magnetron is sensitive to the phase of the reflected wave. The whole system is more stable if the reflected wave decreases the generator load.

A simple scheme (Fig. 15a) employs a dissipative load switched to the transmission line. The distance between the load and the microtron cavity is equal to an odd number of quarter wavelengths. For a detuned cavity or at the beginning of the operational pulse, the load decreases the reflected wave coming back to the generator. When the cavity is tuned, only part of the total power is used in the microtron cavity. This method allows 50 - 70% of the available power to be brought into the cavity.

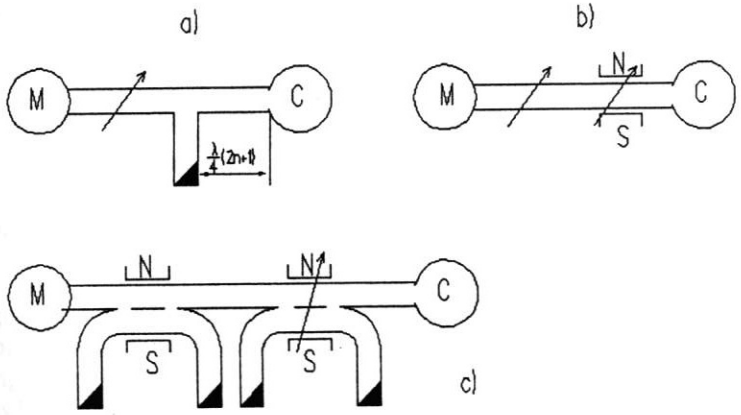


Figure 15: Methods of coupling between magnetron and microtron cavity. C - microtron cavity, M - magnetron.

The coupling with the cavity is simple if a ferrite isolator or circulator is used. Isolators are used for small machines and allow use of nearly 90% of the output power (Fig. 15b). The isolator does not provide ideal decoupling of generator from cavity, and the reflected wave still comes to the generator. If a phase of the reflected wave unloads the magnetron, a pushing of frequency, however small, has sufficient stabilizing effect upon the system.

For higher RF power a network employing circulators is used. In the two-circulator design (Fig. 15c), the first is operating at constant magnetic field bias and provides practically ideal decoupling of generator from load, and the second has a controlled magnetic field bias and works as a variable attenuator. The magnetron is working at maximum output power and efficiency and its frequency practically does not depend on load variations. Since the pushing of the frequency is negligible, the requirement for stability of the difference between resonance frequency and frequency of the magnetron will be higher.

3 The Travelling-Wave Tube

Of the many types of microwave amplifiers, the travelling - wave tube (TWT) has gained wide acceptance because of its broad bandwidth, high gain, high power capability, high efficiency, and good signal characteristics. Travelling - wave tubes are used for communication transmitters and in many types of laboratory equipment. The TWT consists of four major elements, shown in Fig. 16.

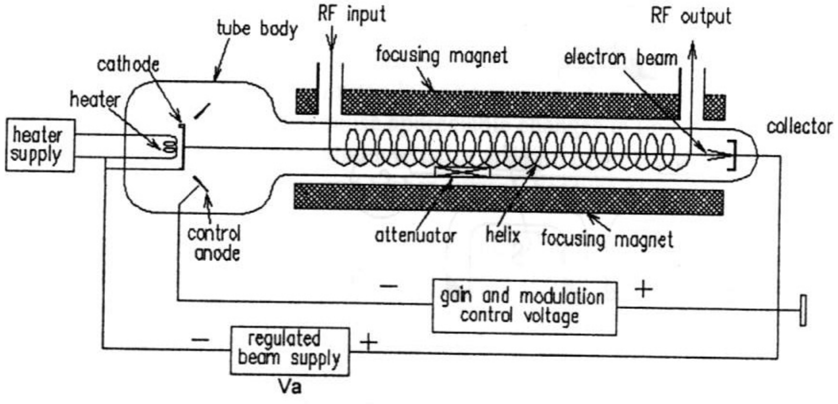


Figure 16: Schematic drawing of the travelling - wave tube.

They are an electron gun, a microwave interaction structure where the electron beam and the microwave signal interact, a magnetic focusing structure that confines the electron beam so that it moves through the interaction structure, and a collector that dissipates the energy in the electrons which originates at a heated cathode and is shaped by the electrostatic and magnetic focusing fields.

A stream of electrons is emitted by the cathode of the electron gun and accelerated by a voltage V_a of the regulated beam supply. A focusing magnet forms a thin beam moving along the axis of the structure. Suppose the structure has the form of a helix. The input RF signal creates a wave that moves along the helix turns with a speed close to the speed of light. This wave produces a travelling electric field at the helix axis.

The speed of this field V_{ph} is much lower than the speed of light c (usually around $c/10$) and is

$$V_{\rm ph} = c \cdot \frac{S}{\sqrt{(2\pi a)^2 + S^2}}\,, \qquad (22)$$

where S is the helix pitch, and a is the helix radius.

The accelerating voltage V_a is chosen so that the speed of the electrons is close to V_{ph}. The condition for that is

$$V_a = \frac{m}{e} \cdot \frac{V_{\rm ph}^2}{2} \quad \text{(non-relativistic case)}, \qquad (23)$$

where m and e are the mass and charge of an electron.

It follows from calculations that the speed of the electrons should be slightly higher then the speed of the wave if the input signal is to be amplified, though in a "cold" (without beam) system exact synchronism is provided. This assertion has a simple physical meaning: if the electrons are travelling at the same rate as the wave, bunches are formed at the place where the electric field is zero, and where a decelerating field is just ahead of the bunch.

The current induced in the wave propagation structure would have a phase shift of $\pi/2$ in relation to the voltage and would be reactive. This effect results in lower wave speed in the structure, because the induced current, while going $\pi/2$ ahead the field voltage, creates a capacitance load of the structure. The speed of the bunch will be a little higher than the speed of the wave and all electrons will be moving ahead in relation to a wave with a small speed equal to the difference. As a result, the bunch center will come into a decelerating area of the wave and start to transfer its kinetic energy to the electromagnetic field of the wave. The wave amplitude will grow exponentially.

The gain is proportional to the tube length, but in reality it is limited. One of the reasons is that the microwave signal at the tube output can be reflected back by a mismatch on the output line. This can cause regenerative gain variation or even oscillation. To avoid this condition most TWTs use an attenuator near the center of the circuit length. The attenuator can include physical severence of the circuit into two or more sections or only carbon attenuation to absorb any reflected power. Usually the attenuation factor for a "cold" system is 10 - 20dB higher then the total gain of the tube. The real gain of the TWT is in the range of 30 - 50dB.

One of the important advantages of the TWT is that of great bandwidth, which is 20 - 50% of central frequency and more. A typical frequency response of a TWT with helix wave propagation structure versus relative frequency is shown in Fig. 17.

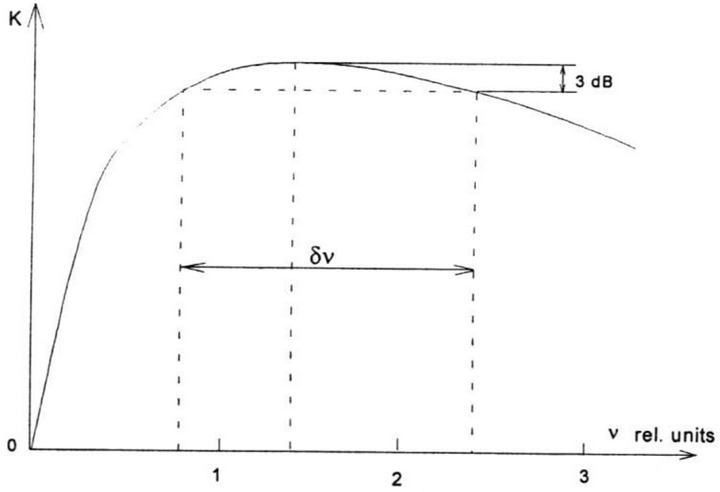


Figure 17: Frequency response of TWT with helical wave propagation structure.

It follows from experience that the frequency bandwidth is actually limited by technical circumstances. Matching of input and output of the tube in a wide frequency range is a difficult problem.

While electrons advance in a decelerating field, their speed drops and becomes even smaller than the speed of the wave. Thus the condition for amplification of the travelling wave is violated. Electrons get back into the accelerating field and start to take back the energy from the wave. Therefore the efficiency and tube gain drop. Real efficiency of a power TWT would not exceed 30 - 40%. It is possible to increase the efficiency by using wave propagation structures that vary the wave speed along the circuit. This method and some others allow increasing the efficiency up to 50% and higher.

The noise factor is very important for amplification of low-level signals. Special types of TWT were developed that use various mechanical and electric configurations and technology. The noise factor of these tubes may be 3dB and less.

Amplitude characteristic curves showing the dependence of output power and gain on input power are plotted in Fig. 18.

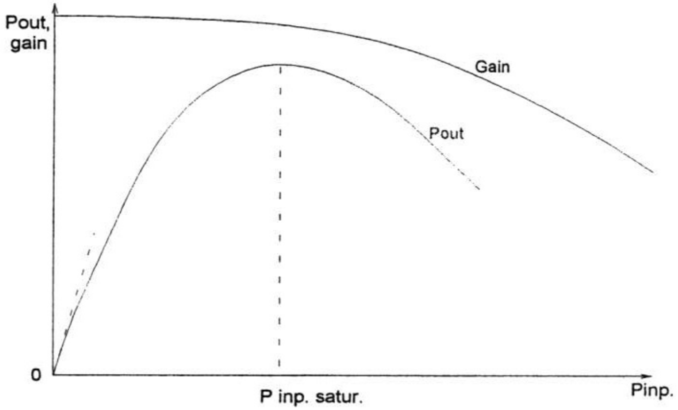


Figure 18: TWT output power and gain versus input power.

At low input power the P_{in} vs. P_{out} curve is linear, and the gain is constant. Then the output power saturates and the gain decreases. However, the point for maximum efficiency is near the maximum output power.

The phase difference between input and output signals of the TWT depends on the input power. It may be explained by a greater drop of the bunch's speed for a higher input signal. This results in slowdown of the structure wave and an increase of output signal delay. The data sheet gives this dependence as AM to PM conversion. Typically it is 2-4° for 1dB of input power.

4 Magnicon: Microwave Generator with Circular Deflection of Electron Beam.

The magnicon design is shown schematically in Fig. 19. A continuous electron beam from the electron source 1 reaches the circular deflection cavity 2, where it is deflected at an angle α_0 by an RF magnetic field rotating with deflection frequency ω. The field distribution in the cavity is shown in Fig. 20. In the drift space, the electron trajectories separate from device axis, and then enter the stationary magnetic field B_z of the solenoid 3. While entering the magnetic field, the longitudinal velocity of the electrons is transformed into rotational transverse velocity (Larmor motion), and the degree of the transformation is characterised by the pitch angle α. Further on, travelling along helical trajectories and steadily changing their entry point into the output cavity 4, the electrons excite an RF wave in the cavity that rotates in synchronism with the entry point of the electrons (TM_{110} oscillation mode, Fig. 20) and transfer their energy to this wave. If the cyclotron frequency Ω is close to the operating frequency ω (i.e. to the circular deflection frequency, to which the cavity is also tuned), and the direction of the cyclotron rotation coincides with that of the deflection device, then the interaction can remain effective during many periods of RF oscillation.

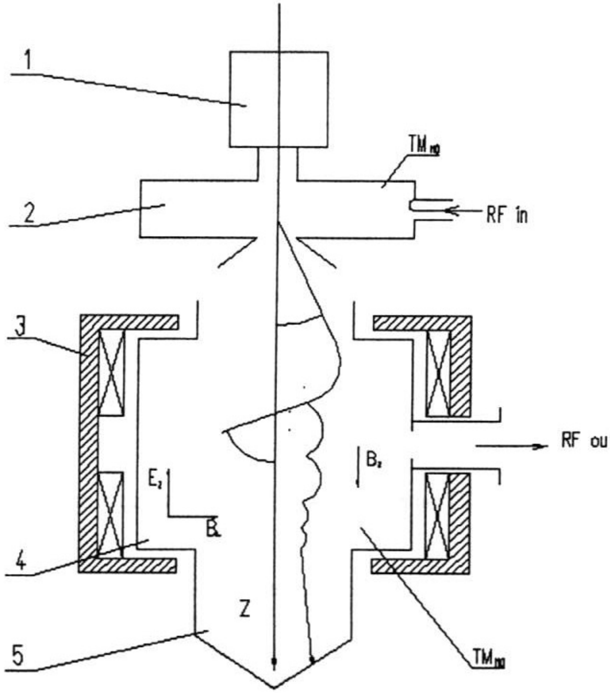


Figure 19: Schematic of the magnicon: 1) source of electrons; 2) circular deflection cavity; 3) solenoid; 4) output cavity; 5) collector.

The particles' energy is transferred to the electromagnetic field on the magnicon output cavity because their transverse velocity decreases, while their axial velocity remains almost constant. This can be easily explained by using as an example the deceleration of a nonrelativistic electron rotating in a homogeneous static magnetic field around the cavity axis. The fields in the cavity are known to have the following relations: $E_z = \omega r \bar{B}_\perp$ (r is the radius). When the cyclotron frequency coincides with the operating frequency, and hence the transverse velocity component is $V_\perp = \Omega r = \omega r$, then $F_z = e \cdot (E_z + V_\perp B_\perp \equiv 0)$.

Thus the transformation of the transverse velocity into longitudinal velocity, which takes place in the cavity under the action of B, is fully compensated by the decelerating effect of E_z. As a result, the limiting electron efficiency is

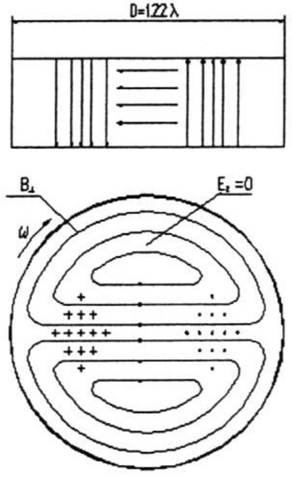


Figure 20: Distribution of electromagnetic field in output and deflection cavities. (TM_{110} mode)

determined by the efficiency of the election energy transfer into rotational motion at the entrance into the magnetic field (i.e. by the pitch angle α) and is equal to $\eta_e \approx \sin^2 \alpha$.

In a magnicon, the electrons are not rotating around the cavity axis, and the longitudinal force is equal to zero "on average" for the period of the RF oscillations. This nevertheless does not change the character and efficiency of the interaction.

A long interaction and the resulting length of the output cavity lead to an essential decrease in RF field strength, in ohmic losses and in specific heat release. In addition, the large hole made for the beam in the center of the cavity end walls combined with the "magnetic accompaniment" essentially eliminates the problem of current interception. Thus, the magnicon can efficiently produce high power in the short wavelength range.

This type of microwave generator was invented at the Budker Institute of Nuclear Physic, Russia. Several magnicons were built and tested there. The main experimental parameters of one of the magnicons are listed in below.

Operating frequency, MHz	915
Beam voltage, kV	300
Beam current, A	12
Beam power, MW	3.6
RF pulse width, μs	30
Output power, MW	2.6
Efficiency, %	73
Gain dB	30

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