THE MAGNICON: A NEW RF POWER SOURCE FOR ACCELERATORS

Oleg A. Nezhevenko
Institute of Nuclear Physics, Novosibirsk, 630090, USSR

INTRODUCTION

In the second half of the 60th the Institute of Nuclear Physics (INP) at Novosibirsk faced the problem of creating a high-power RF generator for the electron-positron storage ring VEPP-4. In the course of research work on this problem G.I. Budker invented a new RF power source — Gyrocon. [1, 2]. The gyrocon like many other devices (e.g. klystron) comprises an electron source, an input cavity for the beam modulation, a drift space and an output cavity for the electron deceleration. But unlike other RF tubes, in gyrocon the beam is not bunched, but is modulated by its circular deflection. The deflected electrons move along straight lines making a cone surface and are passed through a circular slit to the output cavity, which is a rectangular waveguide formed in a ring. With their entering point in the output cavity being continuously changed, therein the particles excite a wave travelling along the azimuth with a decelerating electric field in the point of beam passage (TE_{10} oscillations). The employment of a relativistic beam and the absence of bunching provides for the gyrocon high power and high efficiency.

Experimental parameters of all existing gyrocons are listed in Tabl. 1. The test results have proved the feasibility of RF power sources based on gyrocons and their applicability in accelerators and storage rings. At the same time there emerged problems usually arising in the course of development of a high power and high frequency gyrocon. Some of these problems are connected with overheating and breakdown of the cavities due to the decrease in their size. Another restriction is bound up with the fact that it is hard to pass a beam (in the absence of magnetic focusing) through the slits in the output cavity walls due to the narrowing of the slits and shortening of the distance between the slit edge and the beam «boundary». The problems with the beam passage make it impossible to reduce the energy of electrons (as, for example, in [5]) which could improve the cavities function.

An attempt to overcome these problems has resulted in the creation of a new RF power source with a circular deflection of the electron beam — Magnicon [6, 7].

1. OPERATION PRINCIPLE OF THE MAGNICON

The magnicon design is schematically given in Fig. 1. A continuous electron beam from the electron source 1 reaches the circular deflection device 2 to be deflected there at an angle α_0 by an RF magnetic field rotating with a deflection frequency (ω). The field distribution in the cavity is shown in Fig. 2. In the drift space electrons deviate from the device axis and get into a stationary magnetic field (B_z) of the solenoid 3. While entering the magnetic field the longitudinal velocity of the electrons is transformed into a rotational transverse one, and the degree of the transformation is

Table 1

Gyrocon	Initial	CW VEPP-4	Pulsed*) VEPP-4	Pulsed Balakin's	Pulsed Los-Alamos
Frequency, MHz	430	182	430	7000	450
Power, MW	0.6	0.4	65	60	0.15
Pulse width, μs	20	10	0.7	50	
Repetition rate, pps	0.1		1	1	
Beam voltage, kV	320	240	1600	1300	82
Efficiency, %	65	60	75	25	23
Gain, dB	7	17	26	60	
References	[3]	[2]	[2]	[4]	[5]

*) In operation since 1978.

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characterized by the pitch angle α. Further on, travelling along a helical trajectory and steadily changing their entering point in the output cavity 4, the electrons excite a wave in the cavity travelling along the azimuth (TM_{110}) oscillation mode, Fig. 2) and transfer their energy to this wave. If the cyclotron frequency (Ω) is close to the operation one (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 oscillations.

The particle energy is transferred to the electromagnetic field in the magnicon output cavity due to the decrease in the transverse component in its velocity at a practically constant longitudinal one. It can be easily explained 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 $Ez = -\omega r B_\perp$ (r is the radius) and in case the cyclotron frequency coincides with the operation one and, hence, the transverse velocity component is $V_\perp = \Omega r = \omega r$, then $F_z = e \quad [E_z + V_\perp B_\perp] \equiv 0$. Thus, the transformation of the transverse velocity into the longitudinal one which takes place in the cavity under the action of $B_\perp$ is fully compensated by the decelerating effect E_z. As a result, the limiting electron efficiency is determined by the efficiency of the electron energy transfer into the rotational motion at the entrance into the magnetic field (i.e. by the pitch angle α) and is equal to $\eta_e \approx \sin^2\alpha$.

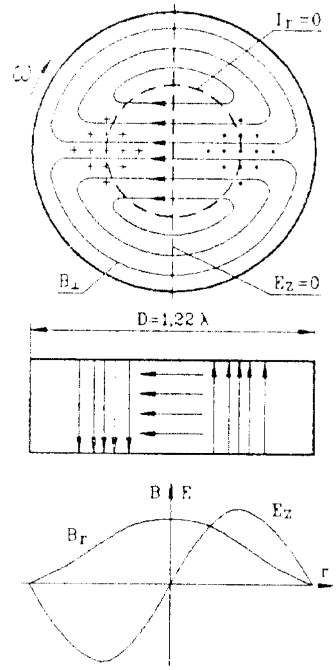

Fig. 2. Distribution of electromagnetic fields in magnicon cavities.

A long interaction and the resulting length of the output cavity lead to an essential decrease in the RF field strength, in ohmic losses and in a specific heat release. Besides, the large holes made for the beam in the centre of the cavity end walls (their diameter is equal approximately to two Larmor ones) in tandem with the «magnetic accompaniment» practically removes the problem of the current interception. Thus, the magnicon, if compared to the gyrocon, provides for attaining higher powers at shorter waves, with the high efficiency characteristic of this class of RF power sources being preserved.

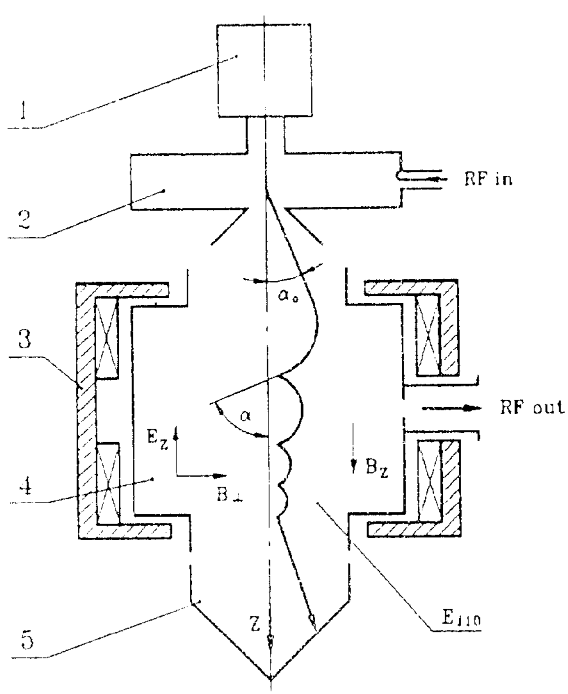

Fig. 1. Schematic of the magnicon: 1—source of electrons; 2—circular deflection cavity; 3—solenoid; 4—output cavity; 5—collector.

2. MAGNICON OUTPUT CAVITY

1. In the general case the problem cannot be solved analytically, but the interaction peculiarities can be studied while solving a simplified problem of motion of a thin nonrelativistic beam in given electromagnetic fields of a perfect (with no holes) cavity. The solution of equations of motion [7, 8] shows that the electron deceleration in a rotating wave TM_{110} at a resonant longitudinal magnetic field B_z (i.e. $\Omega = -\omega$ [1)], $\Omega = e/m_0 B_z$ is the cyclotron frequency, ω is the operation frequency) is accompanied by a change only in the transverse particle velocity ($V_\perp$) while the longitudinal one (V_z) during the period of RF oscillations remains unchanged:

$$V_\perp = V_{\perp 0} \pm \Omega_{RF} \; V_{z0} t, \quad V_z = V_z - (\Omega_{RF}/\Omega) \; V_\perp \sin \omega t. \tag{1}$$

1)The sign «minus» corresponds to the coinciding direction of the electron cyclotron rotation and the wave rotation.

Here: $V_{\perp 0} = V_0 \sin\alpha$, $V_{z0} = V_0 \cos\alpha$, $V_0 = \beta_0 c$ is the initial velocity, α is the pitch angle, $\Omega_{RF} = (e/\gamma_0 m_0) B_\perp$, $B_\perp$ is the RF magnetic field in the region of particle motion (Fig. 2).

From (1) it follows, that V_z is oscillated with an amplitude depending on the relation $B_\perp V_\perp / B_z V_{z0}$ (the lower the relation, the lower is the amplitude). From (1) it also follows, that in the course of deceleration $V_\perp$ is linearly decreased with time and the trajectory of a single particle makes a helix with a constant step and a decreasing radius. The helix axis is parallel to that of the cavity and the distance between them is equal to the initial Larmor radius R_L (Fig. 3). An instant picture of the beam position in the output cavity

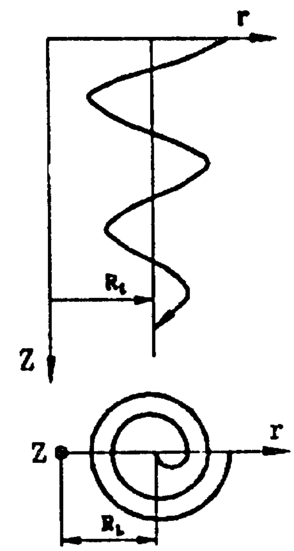

Fig. 3. Electron trajectory in the output cavity.

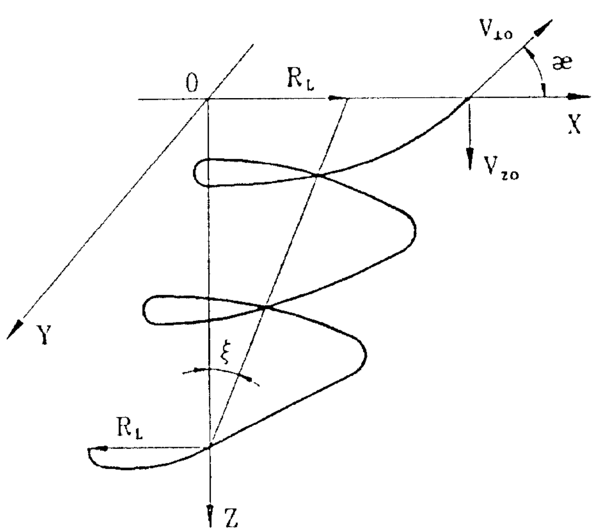

Fig. 4. The instantaneous position of the beam in the output cavity.

(Fig. 4) shows a helix with a constant radius, which axis forms an angle $\xi = \mathrm{arctg}\,(\mathrm{tg}\,\alpha/\theta)$ with the axis of the cavity ($\theta = \omega h / V_{z0}$ is the angle of flight of the electron in a cavity with a height h).

The RF field value optimal for deceleration can be found from (1) on condition, that by the end of passing the cavity the transverse velocity component will decrease to zero·

$$\Omega_{RF}^{opt} = (\omega V_{\perp 0}/\theta V_{z0}) = (V_0/h)\sin\alpha\,. \tag{2}$$

Expression (2) helps to calculate the optimal voltage value in the cavity. In the maximum of the electric field

$$U_{opt} = 2.33(U_0/\beta_0)\sin\alpha\,, \tag{3}$$

where U_0 is the beam voltage. For example, at $U_0 = 200$ kV and $\alpha \approx 90°$ $U_{opt} = 670$ кV and is independent of the cavity height. The possibility of increasing the cavity height enables to reduce the field strength and decrease the losses in the walls[2]. The limiting cavity height is determined by the possibility of selection of parasitic modes and may exceed two wavelengths.

The magnicon can also be operated in the frequency multiplication mode, if in the output cavity the oscillations TM_{m10} are excited with a frequency $m\omega$, m times exceeding that of the deflection [8]. Many-fold multiplication of the frequency can in principle be obtained, an increase in m results in a reduction of RF fields in the region of the beam motion and of practical interest is mostly the frequency doubler. In the output cavity of the frequency doubler a TM_{210} wave is excited (Fig. 5) with a frequency two times exceeding that of the deflection system. The cyclotron rotation frequency of particles is also two times higher than that of the deflection system ($\Omega = -2\omega$). In spite of the absence of the cyclotron resonance a long time interaction takes place due to a quadruple distribution of the TM_{210} oscillation electromagnetic field. The mechanism of interaction of the electrons with the field is similar to that in the amplifier and the maximum electron efficiency is also $\eta_e \approx \sin^2\alpha$. The trajectory of a single electron is also a helix with a decreasing radius, but its axis is bent off the cavity axis [10]. The bend in the helix axis is bound up with the unlinear dependence of the electromagnetic field on the transverse coordinate. The optimal voltage in the cavity at the maximum of the electric field $U_{opt} \approx 3.1\, U_0 \beta_0^{-2}$[3].

[2]The shunt impedance of the cylindrical cavity with a travelling along the azimuth wave TM_{110} [13]: $R_{sh} = 122h^2[\delta(2h+d)]^{-1}$, δ is the depth of the skin layer, d is the cavity diameter.

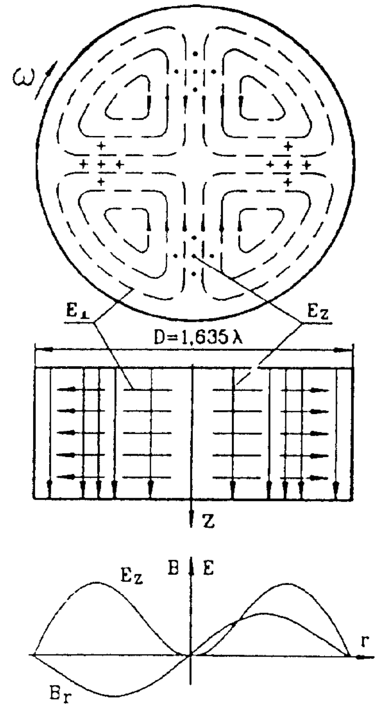

Fig. 5. Distribution of electromagnetic fields in the frequency doubler magnicon output cavity.

2. When for sustaining the synchronism a relativistic beam is used, the accompanying magnetic field ($B_z \sim \gamma$) should be decreased with deceleration. This leads to additional (uncompensated by the action of the electric RF field) transformation of the transverse momentum component into the longitudinal one and, as a result, to a decrease in the efficiency. The maximum value of η_e in this case can be estimated as:

$$\eta_e = (\gamma_0 + 1/2\gamma_0)\sin^2\alpha\,, \qquad (4)$$

where γ_0 is the initial value of the relative electron energy. In an ultra relativistic case η_e is easily shown to tend to 50%.

This problem can be overcome if the synchronism is sustained «in average» [8], i.e. by providing a homogeneous magnetic field in the output cavity

$$B_z \approx \omega m_0/e(\gamma_0 + 1/2)\,. \qquad (5)$$

In this case the longitudinal component of the initial particle momentum is preserved (in average during the cyclotron revolution period), and the expression for the electron efficiency takes the form:

[3] The shunt impedance for a cavity with a TM_{210} wave equals: $R_{sh} = 96h^2[\delta(2h+D)]^{-1}$.

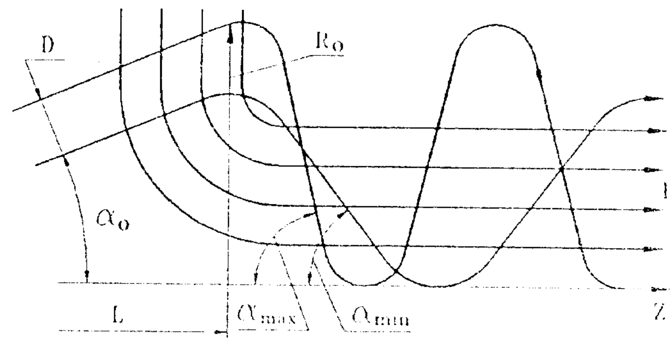

Fig. 6. The finite size beam in the magnetic field of the output cavity.

$$\eta_e = (\gamma_0 - \sqrt{\gamma_0^2 + (1-\gamma_0^2)\sin^2\alpha}\,)\,(\gamma_0+1)^{-1}. \qquad (6)$$

It is evident, that for $\gamma_0 \gg 1$, $\eta \approx 2\sin^2(\alpha/2)$ and large α it approaches 100%. The synchronism «in average» results in limiting the minimum value of RF fields in the cavity and some increase in the cavity voltage (in some sense, equivalent to the transit-time effect). The results of numerical simulation show, that the cavity length can exceed two wavelengths, up to $U_0 = 1 - 1.5$ MV, while voltage exceeds the value calculated in (3) but no more than 1.5 times.

3. The main factor reducing the efficiency and determining the magnicon power is the final beam diameter, which causes the spread of pitch angles (α_{max} and α_{min} in Fig. 6) at the entrance into the accompanying magnetic field of the output cavity and leads to an azimuthal «smearing» of the beam. The electron efficiency in this case is [8]:

$$\eta_e \approx \sin^2\alpha_{min}\left[1 - \frac{D}{2R_0}\right]^2 \left[\frac{\sin\delta\psi/2}{\psi/2}\right]^2, \qquad (7)$$

where D and $\delta\psi$ are the radial and azimuthal beam dimensions, $R_0 = \beta_0\lambda/\pi$ is the Larmor diameter of the external particle. The beam size is first of all determined by particles deviation under the space charge effect in the drift space between the circular deflection system and the entrance to the output cavity. In fact, the drift space (L, see Fig. 6) should be reduced, i.e. α_0 should be increased, since $L = R_0 \operatorname{ctg}\alpha_0 \sqrt{\sin^2\alpha - \sin^2\alpha_0}$.

The ultimate power of the magnicon is determined by the energy of electrons and the deflection angle. As a matter of fact, by setting the electron efficiency we practically impose limitations on the beam size at the entrance in the output cavity. In its turn, this size can be estimated with the help of usual relations for the envelope of a paraxial beam moving in the space free from external magnetic fields [8, 9]. Table. 2 lists the values of the ultimate beam power (P_0) at $\eta_e = 90\%$.

Table 2

U_0, kV	200	300	500	800	1000
P_0, MW (at $\alpha_0=10°$)		0.1	0.5	2	4
P_0, MW (at $\alpha_0=30°$)	0.7	2	10	40	80
P_0, MW (at $\alpha_0=50°$)	4	13	52	220	500

The given estimates at ultimate powers and maximum deflection angles should be considered as approximated, as at a high perveance there will appear other restrictions for the efficiency bound up with the space charge. At the same time at $\alpha_0 \leqslant 30-50°$ the perveance is not very high and these restrictions are not decisive. While estimating η_e besides the finite beam dimensions it is necessary also to take into account the energy spread occurring in the process of circular deflection as well as an additional spread of deflection angles, taking place in the drift space under the action of the space charge. These effects may result several percent decrease in the efficiency. The device efficiency ($\eta=P/P_0$, where P is the output power) is always lower than η_e due to the ohmic losses in the magnicon cavity walls, which might make $1-10\%$ depending on the power and operating frequency. A due account of the mentioned above factors shows, that $\eta \approx 80\%$, which does not seem to be the limit for the magnicon, but serves a good illustration of the device abilities.

The minimum wavelength of the device is determined first of all by the breakdowns and overheating of the output cavity. For absolute deceleration of the transverse velocity component in the output cavity of the magnicon at $\gamma_0 \leqslant 2$ it is necessary to provide a RF electric field [8]:

$$E[\mathrm{kV/cm}] \geqslant (117\eta_e^{1/2}\beta_0^2)\cdot(\lambda[\mathrm{cm}]\sqrt{1-\eta_e}\,(2+0.56\beta_0^2\eta_e-\gamma_0))^{-1} \quad (8)$$

The above restriction is not very rigid. For example, for a CW magnicon at $\alpha=30$ cm and $P=3-10$ MW ($U_o=200-300$ kV) the RF field in the output cavity $E=15-20$ kV/cm, ohmic losses are $20-40$ kW and the losses per surface unite are $10-20$ W cm^2. In the pulsed amplifier at $\lambda=2$ cm and $U_o=500$ кV ($P\sim100$ MW) $E=300$ кV/cm, which value is essentially lower than that obtained for klystrons today [11].

3. CIRCULAR DEFLECTION SYSTEM

1. The circular deflection of an electron beam in the magnicon is performed by a RF magnetic field of a cylindrical cavity with TM_{110} oscillations (Fig. 2). The cavity is excited by an external generator to provide a circular polarization of the magnetic field in the paraxial zone crossed by the deflected electrons. This deflection method has been studied in detail in [9] and has proved reliable in the gyrocon, but the requirement of obtaining larger deflection angles in the magnicon puts forward additional problems. First, the gain coefficient drops, second, the electron beam energy spread grows, which results in the efficiency decrease. These problems have been overcome by accompanying the beam in the deflection cavity by a longitudinal stationary magnetic field; the cyclotron particle rotation in this case should coincide in direction with that of the RF field [12, 13]. The accompanying magnetic field compensates the «lag» of the particles from the rotating plane, in which the electric field

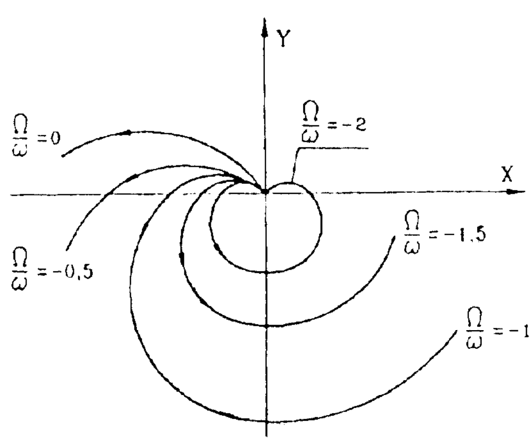

Fig. 7. Electron trajectories in the deflection cavity.

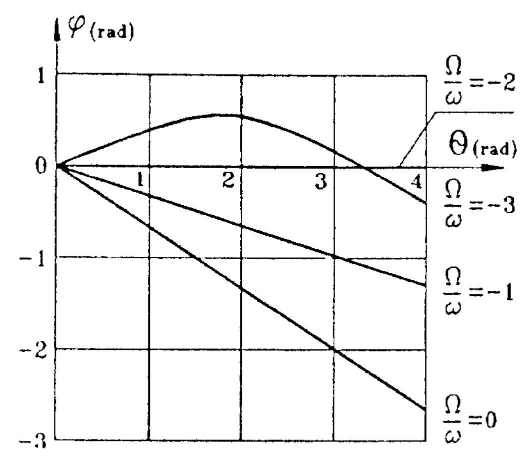

Fig. 8. Azimuth position of electrons in the rotating coordinate system.

strength of the cavity is equal to zero (Fig. 2), and the focusing effect of this field reduces the transverse beam size, and hence, the electron energy spread.

The analysis of the peculiarities of the circular deflection process can be carried out analytically in the approximation of small deflection angles [13], i.e. under the condition, that both the particle velocity in the direction of their initial motion and their energy are preserved. Shown in Fig. 7 are the projections of the particle trajectories onto the plane $x-y$ perpendicular to z. The closed cardioid in the case of $\Omega/\omega=-2$ is obtained at a flight angle $\theta=2\pi$. In Fig. 8 the particle azimuthal coordinate is given versus the flight angle. This dependence is observed in the system of coordinates rotating with a frequency ω, i.e. in synchronism with the RF field. At different values of B_z the motion takes place either in the region of the accelerating ($\varphi<0$ at $\Omega/\omega>-2$) or the decelerating ($\varphi>0$ at $\Omega/\omega<-2$) electric field of the cavity. At $\Omega/\omega=-2$ the electrons move in synchronism with the wave in the plane, where $E_z=0$ and their energy is remained unchanged. The angle of the particle deflection is:

$$\alpha_0=2\frac{\Omega_{RF}}{\omega}\frac{\sin[\theta/2(1+\Omega/\omega)]}{(1+\Omega/\omega)}=\frac{U}{U_0}\sqrt{\frac{\gamma_0-1}{\gamma_0+1}}\frac{1}{2J_1^m}\frac{\sin[\theta/2(1+\Omega/\omega)]}{[(1+\Omega/\omega)\theta/2]}, \quad (9)$$

where $\Omega_{RF}=eB_\perp/\gamma_0 m_0$, U is the voltage amplitude in the cavity at the electric field maximum, $J_1^m=0.582$ is the value of the Bessel function of the first kind first order in the first maximum. It should be noted, that at $\Omega/\omega=-2$ the dependence of α_0 on the flight angle (θ) is similar to that at $\Omega/\omega=0$. At $\Omega/\omega=-1$ the deflection angle is independent of θ.

To calculate the gain coefficient of the device it is necessary to calculate the losses in the cavity walls (P_R) and the power required for the beam acceleration (P_e. The sum of these powers makes the power of magnicon excitation:

$$P_{IN}=P_R+P_e=U^2/2[1/R_{sh}+\mathrm{Re}(\bar{Y}_e)]\,. \quad (10)$$

Here U is the voltage amplitude in the cavity at the maximum electric field, R_{sh} is the shunt impedance of the cavity with a TM_{110} wave (see above), and $\mathrm{Re}(\bar{Y}_e)$ is the real part of conductivity, characterizing the beam-cavity interaction (i.e. electron conductivity). The electron conductivity [7] is:

$$\bar{Y}_e=\frac{J_0}{U_0}\frac{\gamma_0-1}{\gamma_0}\frac{1}{(J_1^m\theta)^2}\frac{\omega}{\Omega}\left\{\left[\sin^2\frac{\theta}{2}-\frac{\sin^2[(1+\Omega/\omega)\theta/2]}{(1+\Omega/\omega)^2}\right]+\right.$$
$$\left.+j\frac{1}{2}\left[\sin\theta-\frac{\sin[(1+\Omega/\omega)\theta]}{(1+\Omega/\omega)^2}-\frac{\Omega/\omega\,\theta}{1+\Omega/\omega}\right]\right\}, \quad (11)$$

where I_o and U_o are the beam current and voltage.

The analysis shows, that for the values of the device power of practical interest the gain coefficient is maximal in the regime, when $\Omega/\omega=-2$ and the power is no more consumed for the beam acceleration ($\mathrm{Re}(\bar{Y}_e)=0$). In this case $P_{IN}=P_R$, and the flight gap is optimized for the minimum ohmic losses ($\theta_{opt}\approx\pi$). A 5-fold gain in the drive power is obtained in this case, compared to the case of a deflection device cavity without magnetic accompaniment, e.g. at $\lambda=30$ cm, $U_0=300$ kV and $P_0=3$ MW, the gain is 10—15 dB.

As it follows from (11), the beam not only loads the cavity but also detunes it. This detuning equals $\Delta\omega/\omega=0.5\rho\mathrm{Im}(\bar{Y}_e)$, $\mathrm{Im}(\bar{Y}_e)$ where ρ is a characteristic impedance of the cavity [9]. The beam reduces the cavity frequency, i.e. the cavity should be preliminary tuned to a frequency higher than the operating one.

In order to use the deflection system with magnetic accompaniment it is necessary to arrange the beam extraction into the drift space without essential losses in the transverse velocity. It is accomplished by placing a flux shield with a small hole for the beam to pass, which considerably limits the magnetic field in the region where the particles travel near the axis, i.e. for $\Omega/\omega=-2$, at a distance $l=(2n+1)B_z\lambda/4$ from the exit of the deflection cavity. The losses in the deflection angle at the particle extraction from a hole with a diameter d are $\Delta\alpha_0/\alpha_0=(\pi d/2\beta_z\lambda)^2$. They usually lead to a not more than 10—15% decrease in the gain [13].

2. An increase in the magnicon gain coefficient can be attained by introducing passive cavities, i.e. similar cavities, which are excited not by an external generator but by the deflected beam.

The calculation of the beam interaction with the electromagnetic field of a passive cavity is performed similarly as for the deflection cavity [13] and for the case of utmost interest ($\Omega/\omega=-2$; $\theta=\pi$) gives the following values for the deflection at the exit from the passive cavity:

$$\alpha_{out}=\sqrt{\alpha_{in}^2+\alpha_p^2-2\alpha_{in}\alpha_p\cos\psi_0}\,. \quad (12)$$

Here α_{in} is the deflection angle at the entrance to the passive cavity; α_p is the beam deflection angle for in the passive cavity; ψ_o is the angle between the particle transverse velocity vector and the vector $B_\perp$ at the entrance to the passive cavity. In this case the active component[4)] of the interaction power [12] is

$$P_e=J_0U_0\sqrt{\frac{\gamma_0+1}{\gamma_0-1}}\,4\pi\frac{\Omega_{RF}}{\omega\lambda}\left(r_0\sin\varphi_0+\frac{2\beta_0 c\alpha_{in}}{\Omega}\cos\psi_0\right), \quad (13)$$

where r_0 is the module of the particle vector radius at the entrance to the passive cavity, φ_0 is the angle between the vector radius and $B_\perp$ at the entrance of particles in the passive cavity, Ω_{RF} is calculated for $B_\perp$ in the passive cavity. R_0, φ_0, ψ_0 and the distance between the cavities l are in the following relation:

$$r_0=(2\beta_0 c\alpha_{in}/\Omega\cos\theta_l)\,;\qquad \psi_0=\theta_l+\varphi_0+\pi/2\,, \quad (14)$$

where $\theta_l=2\pi l/\beta_0\lambda$.

Since after the deflection cavity the deflected partic-

4)The reactive component can be compensated by preliminary detuning the cavity.

Table 3

Operating frequency, MHz	915	Losses in the walls of the output cavity, kW	90
Beam voltage, kV	300	Losses in the walls of the passive cavity, kW	340
Beam current , A	12	Electron efficiency, %	85
Beam power, MW	3.6	RF pulse width, ms	30*)
Current pulse width, ms	50	Gain, dB	30
Repetition rate, pps	1		
Output power, MW	2.6		
Efficiency,	73		

*) This is determined by the oscillation buildup time in the passive cavity.

les move along a helix, the angular excitation rate of the passive cavity is in cyclic dependence on $l(r_0 \sim \cos\theta_l)$. Here one can distinguish two regimes which might present interest in our case: regime of maximum gain and a regime of «summing» the deflection angles (i.e. long-term interaction).

The extremum P_e, and respectively α_p, is reached at $\theta_l = \pi/2$. In this case from (12) it follows: $\alpha_{out} = \alpha_p - \alpha_{in}$. Thus, the maximum gain is achieved when the beam particles enter the cavity near the axis. In this case the gain coefficient [7] is:

$$K_p[\,\mathrm{dB}] = 10\lg\left(\frac{\alpha_{out}}{\alpha_{in}}\right)^2 = 20\,lg\left[19.8\,\frac{J_0}{U_0}\,\frac{\gamma_0-1}{\gamma_0}\,\frac{\beta_0\lambda}{\delta(1+1.22/\beta_0)} - 1\right]. \quad (15)$$

At $\lambda = 30$ cm, $U_0 = 300$ kV and $P_0 = 3$ MW, which corresponds to $K_p \approx 20$ dB; at $\lambda = 10$ cm, $U_0 = 1$ MV and $P_0 = 500$ MW, it is 47 dB. For a further increase in the gain one can use several passive cavities placed in a series along the beam motion.

The regime of «summing» the angles is realized, when $\theta_l = 0$ and $\psi_0 = \pi$ (see (13) and (14)). In this case the cavities should be placed practically close to one another, so that their excitation powers might be practically similar.

4. INITIAL MAGNICON

1. In 1985 at INP (Novosibirsk) there was built and put into operation a 915 MHz magnicon with a pulse duration of 50 μs.

A schematic of the device is shown in Fig. 9. A diode gun 2 with a LaB_6 emitter is used as the electron source. Accelerating voltage is applied to the gun from a pulsed transformer 1 placed in a tank filled with SF_6 under a pressure of 5 atm [14]. After the gun the beam is guided into a circular deflection system 3, which consists of two cavities placed in a longitudinal magnetic field ($\Omega/\omega \approx -2$).

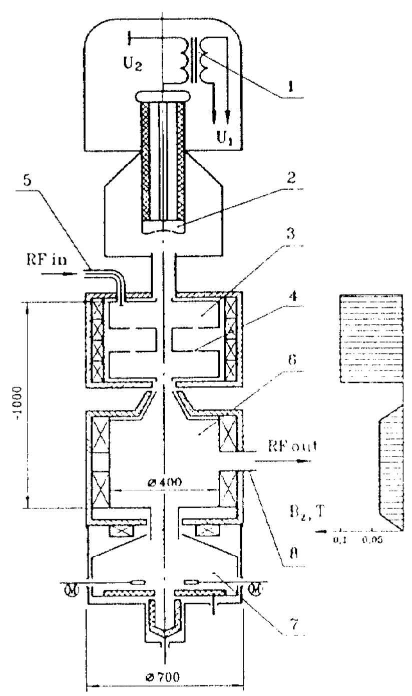

Fig. 9. Schematic of the initial magnicon.

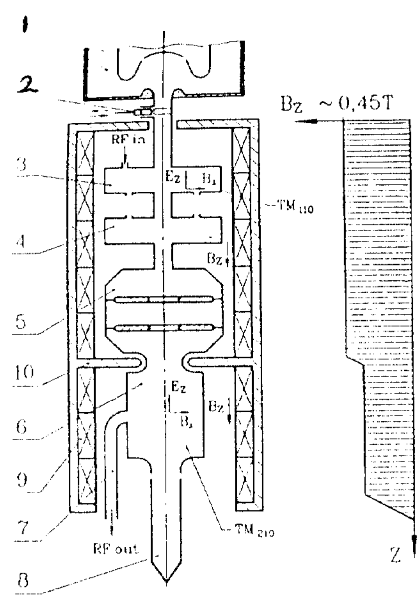

Fig. 10. Schematic of the frequency doubler.

The first cavity is excited by an external generator with the help of two couplers 5 and deflects the beam at a small angle. The second cavity (passive) is excited by a predeflected beam and provides the particle deflection at the required angle ($\alpha_0 = 30°$). The distance between the cavities $\beta_z\lambda/4$ is chosen to provide the maximum gain. The beam is extracted from the magnetic field near the device axis through a hole in the flux shield. After its flight in the drift space the beam gets into an output cavity 6 (the magnetic field distribution is shown in Fig. 9) and then into a collector section 7. The RF power is fed from the magnicon through two waveguides 8 placed at 90° along the output cavity azimuth.

The main experimentally obtained parameters of the magnicon are listed in Tabl. 3.

2. The device tuning begins with obtaining a circular deflection of the required quality. After the assemblage the cavities of the deflection system should be carefully trained to eliminate the multipactor. For this purpose the central part of the cavity is separated from its body by a circular slit cut along the nodal line of the radial current (4 in Fig. 9) and is mounted on insulators. A positive potential of 5—9 kV is applied to it, which in the presence of an accompanying magnetic field initiates a cleaning discharge in the cavity.

As is predicted by the theory, there is such a value of the accompanying magnetic field in the deflection cavity at which no power is required for the beam acceleration. The magnetic accompaniment in the deflection system essentially simplifies obtaining a deflection with a low ellipticity due to the gyrotropic properties of the magnetized beam. The gyrotropic effect develops in the form of «autostabilization» of the deflection shape, i.e. in case oscillations with elliptic polarization are excited in the cavity, then in the beam presence their ellipticity is decreased. «The autostabilization coefficient» depends on the difference in conductivity of the resonance system for the following and for the meeting (with respect to the cyclotron particle rotation) wave:

$$G = (|\bar{Y} + \bar{Y}_e^M|)(|\bar{Y} + \bar{Y}_e^F|)^{-1}. \qquad (16)$$

Here $\bar{Y}$ is the cavity conductivity, while $\bar{Y}_e^F$ and $\bar{Y}_e^M$ are the electron conductivities for the following ($\Omega/\omega < 0$) and the meeting ($\Omega/\omega > 0$) wave, respectively (see (11)). In line with (16) the «autostabilization coefficient» is $G = 6.2$ (the measured value is $G \approx 6.5$). If the deflection system comprises several cavities, their coefficients are multiplied and for our case of two cavities we have $G \approx 40$. As a result of this effect even in the case of the field ellipticity in the deflection cavity corresponding to the ratio of the ellipse axes of ~2.5 (in the absence of beam) the measured ellipticity of the deflected beam does not exceed 5%.

For attaining the maximum of the .output power beside optimization of the magnetic field value and loading, there was also changed the longitudinal distribution B_z in the output cavity. In the decreasing to the end of the cavity field (−20%), as has been theoretically predicted, the interaction efficiency is lower ($\eta_e = 78\%$). The maximum power and efficiency ($\eta_e = 85\%$) have been obtained in the case, when the field is built up to the cavity end (+15%), i.e. when some additional longitudinal energy of particles is transferred to the transverse one The electron efficiency is determined from: $\eta_e = (P + P_{oc} + P_{pc})(P_0)^{-1}$, where P is the output power, P_{oc} are the ohmic losses in the output cavity and P_{pc} are the losses in the passive cavity walls. It should be noted, that in case the cavities are made of copper, the efficiency grows by 5%, i.e. it makes $\eta = 78\%$.

The magnicon power decrease at variation of the output cavity loading is not large and makes approximately 10% at a two-fold change in the output cavity shunt iompedance. The advantage of the magnicon, which is worthy to of being mentioned, consists in the absence of the reflection of electrons in the output cavity at its deloading.

The phase and the amplitude stability of the magnicon have been studied, which turned out to be rather high. The results are given in Tabl. 4.

Table 4

$\frac{\Delta P}{\Delta U_0/U_0}$, dB/%	$\frac{\Delta P}{\Delta B_z/B_z^{*)}}$, dB/%	$\frac{\Delta\varphi}{\Delta U_0/U_0}$, deg/%	$\frac{\Delta\varphi}{\Delta B_z/B_z^{*)}}$, deg/%	$\frac{\Delta\varphi}{\Delta P_{IN}}$, deg/dB
~0.1	~0.03	~2	~3	~4

*) In the output cavity.

Table 5

Operating frequency, GHz	7	Beam current, A	240
Power, MW	60—70	Efficiency, %	60—70
Pulse duration, μs	2	Drive frequency, GHz	3.5
Repetition rate, pps	5	Gain, dB	50
Beam voltage, kV	420		

Besides the described above experiments (when the magnicon operated with damping loads) the device has been successfully tested with the accelerating structure of the racetrack microtron.

5. X-BAND PULSED MAGNICON

1. The performed above analysis proves the feasibility of a 300-1000 MW X-band pulsed magnicon. But the classical scheme of the device, when the main transfer of the longitudinal electron velocity in the transverse one is performed when the particles enter the accompanying magnetic field of the output cavity, requires the presence of a drift space between the deflection system and the output cavity, which limits the current and requires rather a high beam voltage ($U_o = 1.5-2$ MV).

As a prototype for the RF power source of future linear colliders there has been developed at INP an advanced magnicon scheme providing a by an order of magnitude higher perveance compared to that of the classical one. The device is a frequency doubler, which lacks the drift space between the deflection system and the output cavity, with the deflection angle required for attaining the high efficiency being made directly in the deflection system.

2. The schematic of the device is given in Fig. 10, and its design parameters are listed in Tabl. 5. The basic elements of the device are the electron source, the cavity system, the collector and the solenoid.

The cavity system consists of a circular deflection system and an output cavity. The deflection system comprises cavity 3, in which TM_{110} oscillations are excited by the leading RF generator, and two cavities 4 and 5, excited by the electron beam. The central part of the wall between cavities 3 and 4 is insulated from the body, which makes it possible to apply to it permanent voltage for initiating the cleaning discharge and suppressing the multipactor. Cavity 5 is specially designed for obtaining a larger deflection angle at reasonable values of deflecting fields. It consists of three TM_{110} wave cavities coupled in a chain with a step $\beta_z/2$ [5] with opposite phase oscillations in neighbouring cavities. Such a cavity provides for the use of the «angle summing» regime and for obtaining $\alpha_0 \approx 60–65°$ only at E = 200–250 kV/cm^2, required for the high efficiency.

The output cavity 6 is approximately 2λ long, which provides $E=250$ kV/cm. The power is transferred through two connecting coupling holes shifted by 135° along the azimuth. Then it is transferred through waveguides to the load. Collector 8 is insulated from the earth for measuring the beam current. The longitudinal magnetic field ($B_z \sim 0.45$ T) is induced by a solenoid 9. Since the magnetic fields in the circular deflection system and the output cavity are somewhat different (Fig. 10) and require independent tuning for the experimental study, the solenoid is supplied with a special dividing flux shield 10. The electron source 1 contains a diode gun, a step-up pulsed transformer and a modulator. The electron gun [15] is based on a 12 cm in diameter oxide cathode. The main peculiarity of the gun is a high electrostatic compression of the beam (over 1000:1 in area). The electric field strength on the focusing electrode is approximately 140 kV/cm. For the protection of the oxide cathode during routine devacuuming of the device serves a slide vacuum valve 2 with a teflon gasket.

3. At present the electron gun has been tested. During this run there were obtained: a power $P_0 \approx 100$ MW at $U_0 = 430$ kV and $I_0 = 240$ A, a perveance of 0.82, a pulse duration of 2 μs and a repetition rate of 1 pps. The beam diameter measured in the crossover region was 4–4.5 mm. The measurements were performed by burning—through of a thin metallic foil.

Besides, there was measured the beam envelope in the magnetic field of the magnicon solenoid at $B_z = 0.45$ T. The measurements were carried out with the help of a special device with movable graphite diaphragms and metallic pipes 5.7 and 8 mm in diameter. In the course of measurements there was attained a 99% current passover of the current through a 5.7 mm in diameter and 25 mm long pipe. The measurements of the envelope showed that in the pulsation maximum the beam diameter was 3.6 mm (i.e. the area compression exceeds 1000:1), while in its minimum the beam diameter was 2.4 mm (the energy density is 5 кJ/cм^2). The measured beam parameters are close to calculated ones.

The resonance system has just been manufactured and now is being prepared for tests.

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[5] As a matter of fact, the step is alternating, as with the particle deflection β_z decreases.

CONCLUSION

The results obtained in the course of the magnicon creation and study, as well as the calculations and the development of various schemes of the device performed have shown, that the magnicon abilities are characterized by the following parameters:

1. A power of up to 5–10 MW in the CW mode (at $U_0 = 200-300$ kV) and up to 500–1000 MW in the pulse mode (at $U_0 = 0.8-1.2$ MV).
2. An efficiency of about 60–80% (depending on the power and frequency).
3. A wave length range from 2–3 cm up to 0.5–1 m (the frequency decrease is limited by the size growth).
4. A high gain ($K = 30-60$ dB).
5. A relatively narrow frequency band ($\Delta\omega/\omega < 0.5\%$).
6. A high amplitude and phase stability.

These characteristics point out good outlooks for the magnicon application both in accelerators and other areas of microwave power engineering. As to communication systems, the utilization of the magnicon here will be reduced to the cases when it is required to have a higher power rather than a broad frequency band.

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