HIGH-POWER X-BAND PULSE MAGNICON

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The key problem for linear colliders is to desigh efficient pulse RF sources at a power of 300—1000 MW in a centimeter wave range. A novel RF generator with electron beam deflection-magnicon can be one type of the devices with the required parameters [1].

An X-band magnicon has been designed at the Institute of Nuclear Physics as a prototype of such a RF-power source, its designed parameters being listed in Table.

Table

Operation frequency, GHz	7
Output power, MW	60—70
Pulse duration, μs	2
Repetition frequency, Hz	5
Beam voltage, kV	400
Beam current, A	250
Efficiency, %	60—70
Input signal frequency, GHz	3.5
Gain, dB	50

The classical model of magnicon, where the longitudinal velocity of electrons is transformed mainly into the transverse one mainly when the particle enters the accompanying magnetic field of the output cavity, requires a drift space between the deflection system and the output cavity, which limits the value of the current and requires a rather high beam voltage of not less than 1 MV [1].

The developed circuit design of the model allows to increase the beam current and essentially decrease the voltage of the power supply source. The magnicon is a frequency doubler with no drift space between the deflection system and the output cavity, and the deflection

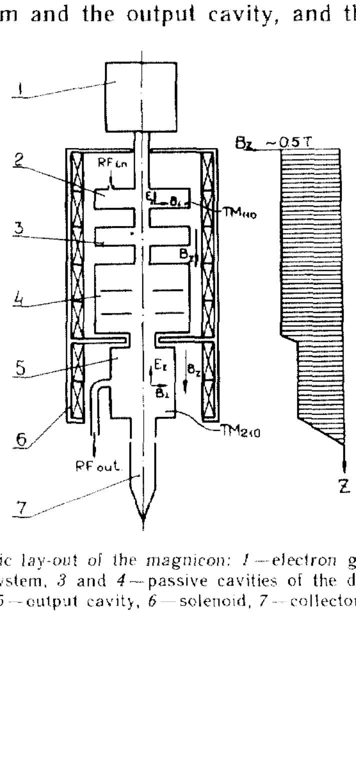
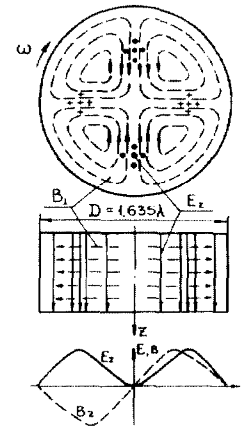


Fig. 1. Schematic lay-out of the magnicon: *1*—electron gun, *2*—cavity of the deflection system, *3* and *4*—passive cavities of the deflection system, *5*—output cavity, *6*—solenoid, *7*—collector.

angle required for attaining a high efficiancy is produced directly in the deflection system (Fig. 1).

To transform the energy of an electron beam into the RF power in the frequency doubler magnicon a cylindrical output cavity is used. An TM_{210} azimuthally rotating field (Fig. 2) is excited in the cavity with a frequency two times higher than that of the deflection system [2].



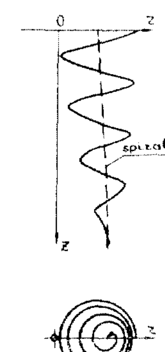


Fig. 2. Distribution of electromagnetic fields in the output cavity.

Fig. 3. Trajectory of an electron in the output cavity.

The beam electrons, having left the deflection system, move along helical trajectories, tangent to the magnicon axis. The cyclotron frequency of the particle rotation due to the longitudinal static accompanying magnetic field (B_z) is approximately two times higher than that of the deflection system $B_z = 2\gamma_m \omega m_0/e$, $\gamma_m = (\gamma_0+1)/2$, γ_0 is the initial value of the relative energy of electrons, e, m_0 are the charge and mass of electron at rest, ω is the drive frequency. Nevertheless, despite the absence of the cyclotron resonance in the amplifier magnicon, the interaction in the output cavity turns out long due to the quadrupole azimuthal distribution of the TM_{210} oscillation electromagnetic field.

The mechanism of interaction of the beam electrons with such a field is the same as in the amplifier magnicon [1]. The transverse RF magnetic field $B_\perp$ transforms a fraction of the transverse electron momentum $P_\perp$ during the cyclotron revolution time in the longitudinal one, while the action of the longitudinal electric RF field compensates for this addend, so that in general the longitudinal component of the initial particle momentum is preserved.

Thus, the maximum electron efficiency is estimated from $\eta_e \approx (\gamma_0 - \sqrt{\gamma_0^2 + (1-\gamma_0^2)\sin^2\alpha_0})(\gamma_0 - 1)^{-1}$. Here, α_0 is the deflection angle at the output of the deflection system.

The trajectory of a single electron is a helix with a decreasing radius, its axis curving away from that of the cavity (Fig. 3). The curvature of the helix axis is bound up with a nonlinear dependence of the electromagnetic field on the transverse coordinate in the region of electron interaction, and is increased with the growth of the particle energy as well as of the deflection angle.

The optical voltage at the cavity, required for the maximum efficiency, in the maximum point of the electric field distribution can be determined from $U_{opt} \approx 3.1 U_0 \gamma_0^2 (\gamma_0^2 - 1)^{-1}$, eU_0 is the initial kinetic energy of electrons. Note that the value of the optimal voltage is independent of the electron efficiency, since this dependence is compensated for by the curvature of the helix axis.

The natural frequency for TM_{210} oscillations is independent of the longitudinal size of the cavity $\omega_0 = 10.27C/D = 2\omega$, C is the velocity of light in vacuum, ω_0 is the angular frequency of TM_{210} oscillations, D is the output cavity diameter. Therefore, the transverse size of the output cavity should be chosen in accordance with an acceptable strength of the RF electric field, sufficiently small Ohmic losses in the cavity walls*) and in accordance with beam dynamics.

The results of numerical simulation of the interaction between the beam and the RF field of the output cavity have shown the possibility of obtaining a high efficiency ($\eta_e \sim 1$) of up to the energy of 1 MeV. As to limiting the longitudinal size of the output cavity, although due to desynchronization it takes place with the growth of energy, nevertheless, it still exceeds the wave length several times.

One of the most serious problems faced while designing the amplifier magnicon [1] is connected with the RF radiation from the output cavity through the end wall central openings made for the beam to pass. As a matter of fact, the radii of these openings should be approximately equal to a double Larmor diameter and with the energy growth, they cease to be cut-off for wave TE_{11}, which is excited in them by TM_{110} oscillations of the output cavity. In the output cavity of the frequency-doubler magnicon TM_{210} oscillations are excited, and the openings in the walls are always cut-off for the TE_{21} wave excited in them. The problem of the feed-back between the deflection system and the output cavity is also practically eliminated, since they operate at different frequencies and oscillation types. It should be also noted, that at a fixed frequency and power of the output signal in the deflection system a lower strength of electromagnetic field as well as a lower constant accompanying longitudinal magnetic field are required compared to the case of the amplifier magnicon.

The main factors limiting the efficiency of the magnicon presented are the momentum spread of the beam electrons in the deflection system, and the limitations caused by a large space charge. The latter, in particular, leads to smearing of the beam contour and to a probable production of a virtual cathode inside the output cavity or collector. However, the estimates show, that for the magnicon at a power of 100—300 MW, operating in a pulsed mode (the energy of electrons is 450—600 keV) it is possible to attain the efficiency of 70—75%.

*) The Ohmic losses in the cavity walls for the TM_{2n0} azimuthally rotating wave are found by formula:

$$P = \frac{(U_{opt})^2}{2R}, \quad R = \frac{95.6}{\delta} \frac{h^2}{(D+2h)},$$

δ is the depth of the skin-layer, h is the longitudinal size of the cavity.

The angular deflection in the device under consideration is performed similarly to that in the [1]. A beam is deflected in cylindrical cavities with a wave TM_{110} travelling along the azimuth, the cavities being placed in a longitudinal static magnetic field, directed so, that the cyclotron rotation of electrons coincides with the direction of the wave rotation, and $|\Omega/\omega| = 2$ (Fig. 1). Ω is the cyclotron frequency.

The basic difference of the presented deflection system consists in the design of the last passive cavity before the output one, in which the electron is deflected at a maximum angle. This unit is chain of three coupled cavities with a E_{110} wave, spaced with a step*) $\beta_z \lambda/2$, with neighbouring cavities having oscillations in opposite phase. The ordering of the cavities in chain as well as the phase shift equal to π makes it possible to realize the mode of «summing up» the deflection angles (i. e. long-term interaction [1, 3]) and produce the deflection angle $\alpha_0 = 60° \div 65°$ required for attaining the high efficiency at a field strength of 200—250 kV/cm. «Cold» measurements of the cavity model has shown that the coupling coefficient $K = 20 \div 25\%$ as well as the difference in the RF fields in neighbouring cavities $\Delta E/E = 20\%$ is easy to obtain.

Beside the decrease in voltage, the chain of coupled cavities reduces also the momentum spread of electrons which takes place at deflection. If we estimate the momentum spread of electrons in a single cavity [1], then in our case $\Delta U_0/U_0 \approx 16\%$, even at $\alpha_0 \approx 30°$. On the contrary, in the case of the chain of cavities, the spread is partially compensated and the estimates show that at $\alpha_0 = 60° \div 65°$ it should not exceed $\Delta U_0/U_0 \approx 10\%$.

The build-up time in the deflection system for operating of the magnicon in the short-pulse regime should be short. But in case of $|\Omega/\omega| = 2$, the cavities remain unloaded by the beam, the pulse rise time is determined from the unloaded decay time and turns out very large. For solution of this problem the magnicon cavities do not require a special device to decrease the quality. It is sufficient to reduce the accompanying field in the deflection system, which will result in a supplementary loading of the cavity of the beam and in the decrease in its quality [1]. A decrease in the accompanying field by 5—10% makes it possible to reduce the decay time compared to the unloaded time decay of the cavity.

In the device under description the number of cavities in the deflection system was chosen to provide a gain of about 50 dB at a pulse rise time of about 0.5 μs. For an effective RF pulse compression at a fixed gain it is necessary to introduce 1-2 more passive cavities.

The experimental set-up comprises two main parts: an electron beam source at a power of 100 MW and the magnicon proper.

The electron source for the magnicon have a diode electron gun a step-up pulse transformer and a modulator. The set-up has employed to the upmost extent the units and blocks designed for the electron source of the first magnicon [7]: the vacuum tank and the high-voltage gun insulator, the gas tank and the core of the pulse transformer.

The diode gun the magnicon is based on the oxide cathode 12 cm in diameter designed for the ELIT-L accelerators [4].

*) The step is, obviously, varying, as β_z is being reduced with the particle deflection.

The main paculiarity of the gun under consideration is the high electrostatic compression of the area (1500:1) of the beam at a small half-angle (36.9°). As a result, the inhomogeneity of the emission from the cathode, as well as the maximum strength of the electric field on the focussing electrode is considerably reduced. Meanwhile, the geometry of the gun electrodes is chosen to obtain a beam with a close to homogeneous distribution of the current density and a minimum transverse emittance.

The pulse transformer is placed in the tank, filled with SF_6. Its Φ-shaped solid core is about 100 cm^2 in cross section. The secondary winding consists of 75 turns of a polyethylene-insulated wire. The winding is made of 2 parallel wires for feeding the cathode heater. The primary winding contains 6 turns and is made of 16 parallel wires, evenly distributed over the frame circumference. The core of the transformer is demagnitized by a pulsed current through the primary winding.

The modulator is made according to the circuit of the double forming line. A hydrogen tyratron (25000 A/50 kV) is used as a commutator. Every half-line has 8 LC-cells with a characteristic impedance of 5 Ohm, consisting of ceramic capacitors (4700 pF, 50 kV).

The schematic design of the magnicon is presented in Fig. 4. The main units of the set-up (beside the source of electrons) are a resonance structure; an electron collector and a solenoid, inducing a static accompanying magnetic field.

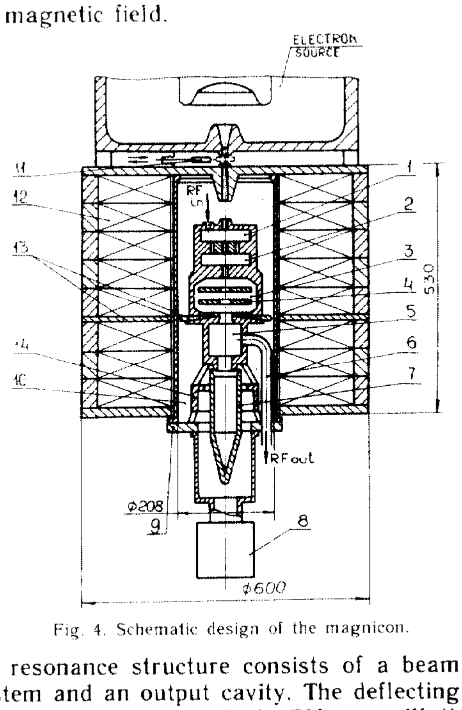


Fig. 4. Schematic design of the magnicon.

The resonance structure consists of a beam deflecting system and an output cavity. The deflecting system consists of cavity *1* in which TM_{110} oscillations are excited by a RF generator, and two cavities *2* and *3*, excited by a beam of electrons. The internal part of the wall between the active *1* and the passive *2* cavities are insulated from the body, which makes it possible to apply to it a DC voltage for initiating the cleaning discharge and suppressing the multipactor. Two flat discs *4* divide the passive cavity *3* into *3* separate coupled cavities with a required field distribution in the region of the particle motion. Each disk is placed on four cylindrical radial stems. The energy from the output cavity *5* is extracted through two waveguides (the cross section of the waveguides is 35×15 mm); these energy outputs are fhifted with respect to one another by 135°, since the output cavity operates by TM_{210} oscillations.

All the parts of the resonance structure, as well as the collector of electrons *7* (insulated from the earch for measuring the running into it electron current) and vacuum pump 8 are installed at the flange *9* of the vacuum tank *10*.

A vacuum slide valve *11* with a teflon seal is used for the protection of the oxide cathode of the electron source in case it is necessary to let the air in.

The axial accompanying magnetic field with an induction of about 0.5 T is produced by the solenoid, placed outside the vacuum tank *10*, and consists of *8* water-cooled coils *12* with a power supply current of 1000 A.

Since the magnetic field strength in the beam deflection system differs slightly from that in the output cavity, the solenoid is supplied with a special dividing magnetic shield *13*. To reduce the number of solenoid coils and there with preserve the required configuration of the magnetic field at the output of the output cavity *5*, a special magnetic pole *14* is introduced in the design.

All the cavities of the device are made of copper, all the parts of the vacuum system — of nonmagnetic stainless steel, the parts of the magnetic system — of a magnetoirresistive 0.1% carbon steel. The electric insulation is made of ceramics, all the demountable vacuum units are supplied with indium seals.

At present the source of an electron beam has been designed, manufactured and tested, while the magnicon is still in the process of manufacturing.

During the test measurements of the electron beam source there was obtained a power of $P_0 = 100$ MW at $U_0 = 430$ kV and $J_0 = 240$ A. The pulse duration was 2 μs. The pulse repetition frequency during the test run was 1 Hz and there arose no problems in the process of operation. The beam measured close to the crossover is 4—4.5 mm in diameter (thus the compression ratio is $\approx 800 \div 1$). The measurements were made by burning through thin matallic foils.

The further program on the experiments at the set-up consists of two stages. The first consists in the starting of the magnicon operation and attaining the maximum power in the mode of operation under and absorbing load. And, the second one consists in testing of the magnicon together with an approximately 25 cm long TW accelerating structure for obtaining the maximum acceleration rate as well as in testing the waveguide system at high values of the RF field strength.

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