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PERFORMANCE OF THE HIGH POWER 7 GHz MAGNICON AMPLIFIER*

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A new microwave amplifier – the magnicon, in which the beam is modulated by varying its spatial position by means of circular deflection is concerned in this paper. The presented device version was developed as a prototype of a microwave power source for linear colliders and it is an amplifier operating in a frequency-doubling mode. The tube design, the problems faced and overcome during investigation as well as the latest experimental results in which a power of 30 MW, efficiency of 35% and pulse width of 0.7 μs have been obtained at operating frequency of 7 GHz are described in the paper.

KEY WORDS: Microwave source, linear colliders, power, efficiency

1 INTRODUCTION

The magnicon belongs to a new class of microwave amplifiers – deflection-modulated devices.[1] This class of microwave sources has been developed at our Institute (INP) since 1967 when G.I. Budker invented a new RF amplifier, the gyrocon,[2] in which a relativistic electron beam is modulated by varying its spatial position by means of circular deflection.

The first gyrocon was developed at INP in 1970 and showed a record electronic efficiency in experimental tests.[1,2] Successful research of the first gyrocon made it possible to build several gyrocons in INP and LANL (USA). For example, the linear electron accelerator was developed in INP and the pulsed gyrocon was built as a RF power source for it, both of which are the main components of electron-positron collider VEPP–4 positron source and demonstrate the world record parameters till now.[1,2] The pulsed gyrocon with a frequency of 430 MHz has a power of 65 MW and efficiency about 75% which provides acceleration of the electron beam with a current of 30 A and energy up to 50 MeV. This installation has been successfully operating for the last 17 years. It has proved that microwave sources with circular beam deflection can be used successfully as a part of accelerating

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complexes. However, investigations have also revealed the gyrocon disadvantages, which mainly concern the beam and cavity operating problems.

Attempts to improve devices of this class have led to the invention and development of a new device, the gyrocon with an "accompanying magnetic field", called the magnicon. The first magnicon was built and tested in the 1980's in INP.[3] A power of 2.6 MW was obtained at 915 MHz with a pulse duration of 30 μs and an electronic efficiency of 85%. During the first tests the magnicon showed efficiency exceeding that of klystrons achieved in the course of over 50 years of its development.

This paper presents an advanced version of magnicon developed in INP as a prototype of the microwave power source for linear colliders. The tube is an amplifier operating at frequency of 7 GHz in frequency-doubling mode.[4,5] This scheme allows to increase the perveance sufficiently compared to the initial magnicon[3] and to obtain an output pulse power of tens and hundreds of megawatts at a reasonable values of beam voltage – 400–600 kV. The magnicon design as well as the problems which appeared during investigation and methods to overcome them together with the latest experimental results are presented below.

2 THE MAGNICON DESIGN

1. The magnicon consists of the following basic units: an electron source, RF system, magnetic system and a collector. RF system consists of two parts: the deflecting system for beam modulation and the output cavity for conversion of the beam energy into the RF energy. A magnetic system provides a long-term interaction between beam electrons and RF fields in the cavities as well as beam focusing.

A schematic diagram of the device is shown in Figure 1. A diode gun 1 based on a 12-cm-diam. oxide cathode is used as an electron source.[6] The main peculiarity of the gun is its very high electrostatic compression ratio (over 1000:1 in area). For the protection of the oxide cathode during routine dismantling of the device there is a vacuum gate valve 2 with a teflon gasket.

The solid beam from the electron source gets into the circular deflection system, which consists of a number of cylindrical cavities located one after the other. In these cavities circularly-polarized TM_{110} mode (Figure 1) oscillations are excited. An electron beam moving close to the axis is deflected by the transverse RF magnetic field, excited in the drive cavity 3 by the drive generator. In the passive (gain) cavities 4, excited by a deflected beam, the further increasing of the deflection angle occurs. The main feature of the deflection system lies in the design of a penultimate cavity 5, in which the beam electrons are deflected to the maximum angle. The penultimate cavity consists of two coupled cavities in which the beam excites the opposite-phase (π-mode) oscillations, thereby enabling the realization of the deflection angle "summing" mode of operation.[1] This enables one to attain a deflection angle $\alpha > 50°$ (which is necessary for reaching high efficiency) at a cavity surface RF field $E \approx 250$ kV/cm. All the cavities are located inside the solenoid 8, which produces a longitudinal magnetic field. For an effective beam deflection it is necessary for the cyclotron frequency of electron rotation in the solenoid field to be 1.5–2 times higher than the drive frequency, and the cyclotron rotation direction must coincide with that of the RF field in the deflection cavities.

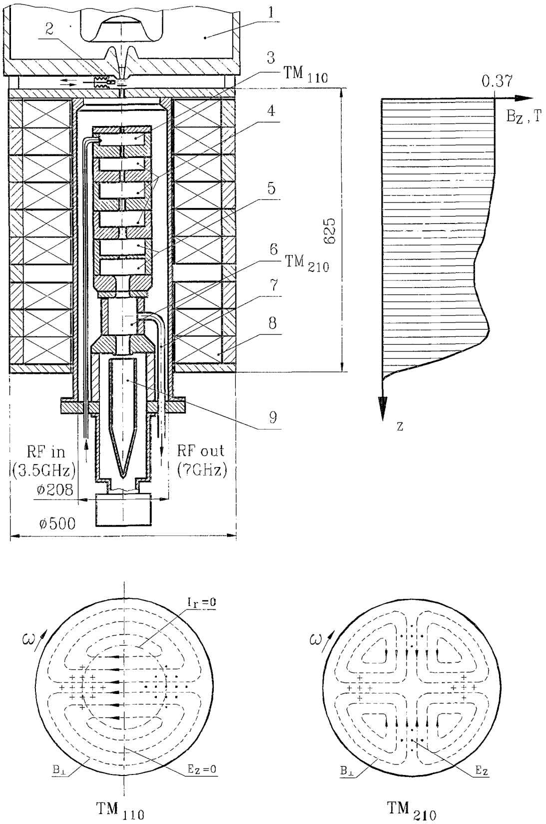

FIGURE 1: Schematic layout of the magnicon: 1 – electron source; 2 – vacuum valve; 3 – drive cavity; 4 – gain cavities; 5 – penultimate cavity; 6 – output cavity; 7 – waveguide (×2); 8 – solenoid; 9 – collector.

Further on, traveling along helical trajectories and steadily changing their entry point into the output cavity 6, the electrons excite an RF wave in cavity 6 with a frequency twice as high as the drive frequency and the wave rotates in synchronism with the entry point of the electrons (TM_{210} mode, Figure 1) and transfers the transverse component of their energy (efficiency $\eta \approx \sin^2 \alpha$) to this wave.[3,5,7] If the cyclotron frequency is close to the operating frequency, i.e. to the doubled drive frequency then the interaction of electrons and RF field of the output cavity can remain effective during many periods of RF oscillations.[3,5,7] Thus, static magnetic fields in the deflection system and output cavity are practically equal. The output cavity is more than 8 cm long which provides $E \approx 250$ kV/cm. The power comes out through two coupling apertures shifted by 135° along the azimuth. Then it is transferred through waveguides 7 to the loads. The collector 9 is insulated from ground in order to measure the beam current.

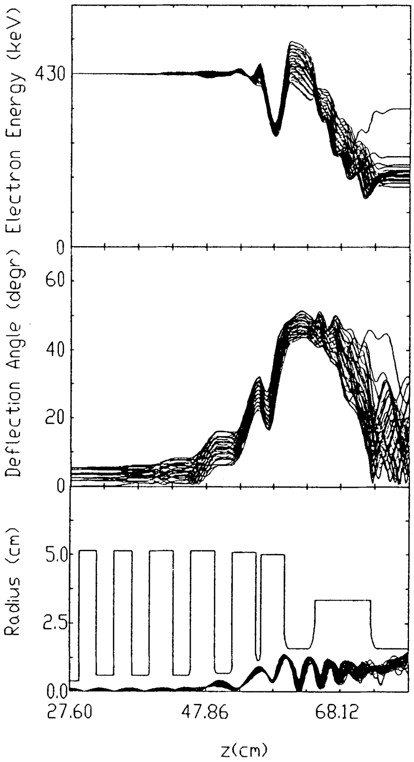

FIGURE 2: Simulation of the magnicon for a 3 mm diameter beam.

2. The design parameters of this magnicon version are listed below:

Operating frequency	7	GHz	Drive frequency	3.5	GHz
Output power	55	MW	Gain	53	dB
Pulse duration	1.5	μs	Beam voltage	420	kV
Repetition rate	5	pps	Beam current	240	A
Efficiency	56	%			

The results of the beam behavior simulations in the process of deflection and deceleration are shown in Figure 2.

The design is based on the detailed preliminary numerical simulations.[8] The physical model considers the beam of finite transverse size, real space distribution of DC magnetic field and real RF fields of the cavities. Those fields were calculated by SAM and SuperLANS2 codes.[9,10] We do not take into account space charge effects and finite beam emittance. The numerical model is based on macro particle method. We have created the codes for both steady state and time dependent simulations. A self-consistent solution during the steady state simulation is obtained by choice of the cavity RF field amplitudes and phases to achieve an overall power balance. Steady state simulations were used for magnicon optimizing and stability analysis. Time dependent code has been applied for transient process investigations.

3 CHALLENGES

There are certain challenges in trying to engineer a practical implementation of this magnicon concept.

1. Some problems appear because of the necessity to have a large deflection angle in the beam deflecting system. This makes it necessary to have large beam holes in the walls of penultimate cavity (the hole diameters must be about four Larmor radii). These holes produce a perturbation of RF field distribution. In particular large transverse electric fields appear near the holes. The action of these fringing fields on the beam dynamics creates two problems.

First, these fields produce beam energy and angle spreads, which lower the efficiency when the beam diameter increases. To obtain high efficiency, it is necessary to use a beam with the minimal initial diameter, i.e. with a diameter close to the Brillouin limit. To overcome this problem, a special electron optics system has been developed. This electron optics system allowed to obtain a beam with a power of about 100 MW ($U = 434$ kV, $I = 236$ A) and with required diameter of 2.5 mm at a scalloping amplitude 10% (in magnetic field $B_z \sim 0.45$ T).[6] In addition to using the beam with minimal diameter it is possible to decrease the efficiency reducing effect through compensation of fringing fields influence in penultimate cavity by means of the action of fringing field at the output cavity entrance. One can see the energy spread compensation effect in Figure 2.

Second, transverse fringing fields decelerate electrons. That is, near the beam holes, electrons transfer energy to the RF field. For a beam current of hundreds of amperes, this can lead to an instability which is specific to magnicon. This instability causes self-excitation of a single cavity in the operating RF mode (TM_{110}), without requiring any external feedback. For coupled cavities the current threshold instability is lower than for a single cavity. It is possible to overcome this instability problem using a special cavity geometry and a nonuniform axial magnetic field distribution along the tube axis. In particular, decreasing the magnetic field in the vicinity of the penultimate cavity (see Figure 1) increases beam loading of this cavity and thus increases the current threshold of the instability.

2. Another way to suppress the operating mode TM_{110} self-excitation is to lengthen the second gap in penultimate cavity. This method allows to obtain a higher gain value and was used in the previous version of frequency-doubling magnicon that allowed to obtain a power of 20 MW and efficiency of 25%.[11] However, attempts to increase the power lead to breakdown in penultimate cavity. As we found out, it is caused by non-linear dependence of interaction power between the beam and RF fields in penultimate cavity on particles transit time, i.e. deflection angle ($v_z = v_0 \cos \alpha$, where v_z is the axial velocity of electrons, α – deflection angle). This non-linearity is revealed as an effect known in theory of non-linear oscillation as "amplitude jumps". The "amplitude jumps" problem can be overcome by

means of the penultimate cavity detuning, however, this leads to a noticeable efficiency decreasing.[12]

3. The optimal length of all deflection system cavities is close to the value when electron transit time is half an RF period. However, in this case it is necessary to keep in mind that the eigen frequency of TM_{431} mode practically coincides with four-fold drive frequency ($f_{431} \approx 4f_{\mathrm{drive}} = 14$ GHz). During the previous magnicon version investigation we observed the autographs of the TM_{431} mode discharge in the first gap of the penultimate cavity.[12] It turned out that in this case the first gap of penultimate cavity operates not only as a deflecting cavity but as an output cavity of the magnicon operating in frequency-multiply mode. In connection with the non-linear dependence of RF fields from radial deviation in the beam passing area ($E_z^{431} \sim r^4$) this effect appears clearly first of all in penultimate cavity, where the deflection angle (hence the electrons deviation from the axis) is maximal.[13] For example, $E_z^{431} \geq 1$ MV/cm at $\alpha \approx 20°$. This problem has been overcome through the choice of cylindrical part of cavities geometry so that the "risky" modes should not be a multiple to the drive frequency.

4. One should keep in mind that for coupled cavities there may also be a klystron-like instability in the TM_{010} mode. In the first design version of this magnicon, three strongly coupled cavities were used as a penultimate cavity. The coupling coefficient was about 20%.[4,5] This cavity was self-excited at 2.6 GHz when the current reached only 50 A. This corresponds to the $\pi/2$ mode, which has a minimal current threshold because of a large bunching distance. In the present design, this problem is solved by using two coupled cavities with small coupling (coupling coefficient is 0.5% for the TM_{010} mode). In addition, the relative difference of the TM_{010}-mode eigen frequencies for those cavities is greater than the coupling value.

5. One should remember that instabilities can also take place in the output cavity. The instability appears largely as a drastic decreasing of efficiency as well as power. This problem can be solved by the selection of static magnetic field value and to some extent output cavity detuning.

4 EXPERIMENTAL STUDIES

1. At the present time, the initial tests of the latest magnicon version (Figure 1) have been carried out. The parameters obtained are listed below:

Frequency	7.006	GHz	Drive frequency	3.503	GHz
Power	30	MW	Gain	55	dB
Pulse width	0.7	μs	Beam voltage	401	kV
Repetition rate	3	pps	Beam current	210	A
Efficiency	35	%			

The oscillograms presented in Figure 3 are: beam voltage (U), signal from the penultimate cavity (PC4) and output signal (OUT1). The output signal (peak power) calibration was carried out by the calorimetric measurements of average RF power.

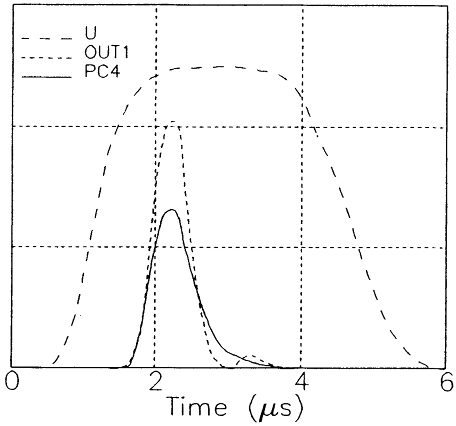

FIGURE 3: The oscillograms.

The magnicon cavities consist of separated copper parts connected with one another by indium seals. This design allows to replace the RF system parts operatively but does not allow to bake-out the cavities up to high temperatures. This leads to long RF condition times for the cavities. In the described experimental studies the main problems were concerned with conditioning of the output cavity, waveguides and loads, that are a single vacuum chamber (there are no ceramic windows). During conditioning self-excitation in the output cavity appeared and after a time disappeared at various frequencies (11.8 GHz, 5.92 GHz and 12.04 GHz, one after another). The first two frequencies disappeared during conditioning, however the self-excitation at the frequency 12.04 GHz is still here and limits the pulse width at a power over 20 MW (at lower power the output signal duration is 1.5 μs). One of the possible reasons of self-excitation is the distortion of RF fields distribution in the output cavity due to presence of coupling apertures with waveguides (see below).

2. The main cause of decreasing efficiency with respect to the designed value is a thicker beam (than the calculated one). In the course of work on the 7 GHz magnicon we examined 7 cathodes. Depending on the cathode quality and gun assembling the beam diameter somewhat varies, however the average $d_{\max} = 2.8$ mm. However, in the present magnicon version the magnetic field of solenoid (8, Figure 1) is 0.37 T rather than 0.45 T, which is the projected value for operating gun. This magnetic field decreasing by 20% leads to the beam diameter increasing up to $d_{\max} = 4$ mm. The calculated efficiency value versus beam diameter $d_{\max}$ is shown in Figure 4. It is clear from Figure 4, that at $d_{\max} = 4$ mm efficiency cannot exceed 42% and for the projected value of 56% it is necessary to have the beam with $d_{\max} \approx 3$ mm. Thus the measured efficiency is 80% of the calculated value for the real beam available now. To improve the situation a new focusing electrode for the gun has been developed, which will decrease the beam diameter to the previous value $d_{\max} = 2.6 \div 3$ mm.

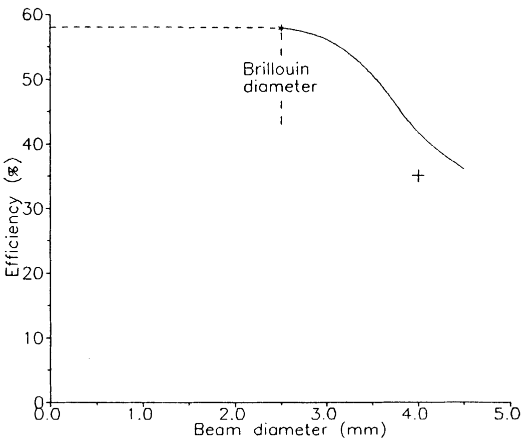

FIGURE 4: The efficiency versus the beam diameter; the experimental point is marked with +.

3. Another cause leading to decreasing efficiency is the RF fields distribution distortion in the output cavity due to the presence of coupling apertures with waveguides. The field maps (2D simulation[10]) for orthogonal TM_{210} modes, superposition of which defines the RF fields distribution in output cavity, are presented in Figure 5. For compensation of the coupling apertures with the waveguides effect (1) there are two protrusions (2) in the present design output cavity, however, their effect is inadequate. One can see that field distribution of these two modes differs sufficiently. The loaded Q-factors of these modes also somewhat differ (180 and 220). As a result the interaction with the beam is found to be irregular along the azimuth that leads to the decreasing efficiency.

This problem can be solved by increasing the number of protrusions. The improved cavity version is being developed now. We also think that a better cavity design can improve the situation with the parasitic modes self-excitation by decreasing the coupling between the beam and non-symmetric parasitic modes.

4. The measured dependence between the output power and drive signal (Figure 6) is in quite good agreement with the simulation results.

It is traditional (beginning with gyrocon) for the oscillations with circular polarization obtaining that the deflection cavity is driven by two signals of equal amplitude through two power inputs separated in azimuth by 90°.[1,14] These signals must also be shifted in phase by 90°. In magnicon the beam is magnetized and its gyrotropic properties lead to the circular deflection "self-stabilization" effect, i.e. if oscillations with an elliptical polarization are excited in the cavity, the ellipticity is reduced in the presence of the beam.[1,3] The experimental tests have verified that in the present magnicon version this wholesome effect shows itself so strongly that one can drive the deflection cavity by one signal (like a klystron) without a loss in output power and efficiency.

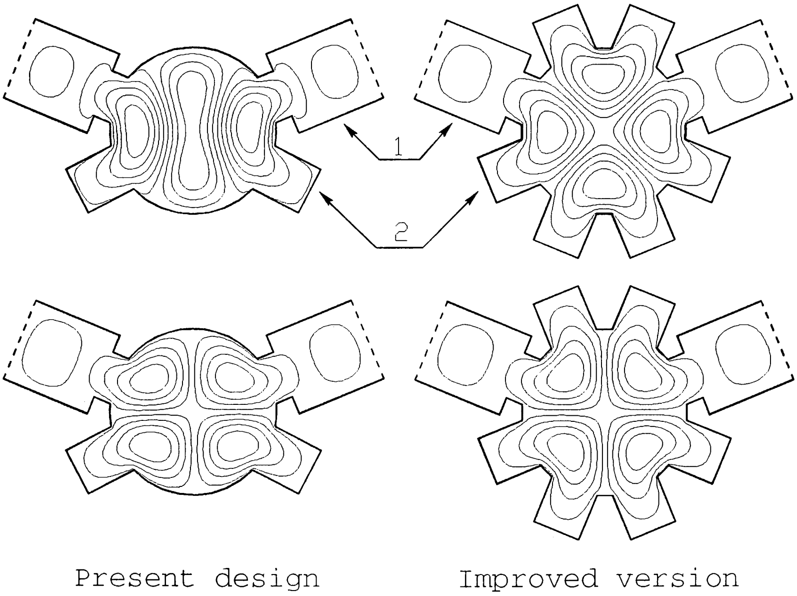

FIGURE 5: Field maps in the output cavity: 1 – waveguides, 2 – protrusions.

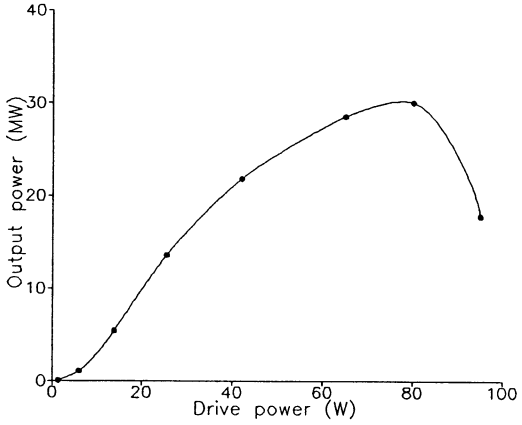

FIGURE 6: The output power versus drive signal.

5 SUMMARY

In the course of 7 GHz frequency-doubling magnicon amplifier investigation a peak power of 30 MW and efficiency of 35% have been obtained in a pulse of 0.7 μs width. The drive frequency is 3.5 GHz and gain is 55 dB. This performance establishes the magnicon as an attractive candidate for linear collider applications.

During investigations many effects interfering with the normal operation of the device were revealed. They are: self-excitation of the penultimate cavity (TM_{010} and TM_{110} modes), harmonics generation, instability in penultimate and output cavities. After eliminating these problems the device behavior is in good agreement with theoretical predictions and simulation results. The main causes of the difference between obtained efficiency and design value of 56% are the relatively thick beam (diameter is 4 mm instead of 3 mm) and RF fields non-symmetry in the output cavity. We are going to eliminate these drawbacks and obtain parameters approaching the designed ones in the nearest future.

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