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A CONCEPT OF A WIDE APERTURE KLYSTRON WITH RF ABSORBING DRIFT TUBES FOR LINEAR COLLIDER

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1 Introduction

It is widely accepted nowadays in the physical community that new generation of electron-positron colliders of TeV range should be a linear one [1]–[4]. To achieve a reasonable length and cost of such a collider, an accelerating gradient of the order of 100 MV/m is needed. The most popular approach to construct TeV linear collider assumes to develop standard klystron and accelerating structure technology operating in X-band. These investigations are under study at SLAC (NLC project), KEK (JLC project), Novosibirsk/Protvino (VLEPP project) [4]. There is significant progress in development of accelerating structure technology, the latest results have shown that accelerating gradient about of 100 MV/m is achievable in the X-band accelerating structure [5,6]. On the other hand, there is rather modest progress in the development of X-band klystrons, output parameters of experimental devices are significantly less than those required [7].

The klystron should have definite parameters. These parameters are very close for all the projects: operating frequency 14 GHz (VLEPP) or 11.424 GHz (NLC, JLC), peak output RF power 50 – 100 MW, pulse duration 0.5 – 1 μs, repetition rate of the order of 100 pps or higher.

The cost of the RF system constitutes significant fraction of the total cost of the linear collider. Number of the klystrons in a 1 TeV linear collider is about of several thousands. Total power consumption of the RF system is of the order of 100 MW. All the elements of the RF power system are complicated engineering devices. To minimize the cost and to increase the efficiency and reliability of the RF system, all its elements (modulators, electrodynamic system of the klystron, focusing system of the klystron, low-power RF system of master amplifiers) can not be considered as independent pieces and one should perform overall optimization.

As for focusing system of the klystron, it should be based on permanent magnets, because this reduces significantly operational cost with respect to electromagnetic solenoidal focusing [8]. The cheapest modulator is considered in the VLEPP project [9]. This concept is based on the use of distributed DC high-voltage power supply. The control of the beam current is performed by means of gridded electron gun [8]. Such an approach requires development of a large aperture klystron, because the electron beam quality of the gridded electron gun is worse than that of the simple diode gun. Another problem of optimization is the choice of the power gain of the klystron. This problem can not be considered independently from the system of low-power RF amplifiers providing synchronized input signals for the klystrons. Here we should remember that semiconductor technology provides the possibility to construct low-cost, reliable and compact X-band amplifiers with output power of the order of 1 W. If the klystron will require a higher level of input power, the system of master amplifiers should be based on vacuum tube devices, which are less reliable and more complicated. Moreover, the problem of precise synchronization becomes more severe at higher level of RF power. Remembering that peak power of the klystron is of the order of 100 MW, we may conclude that the choice of the power gain of 80 dB is the most optimal one.

We see that one of the key elements of optimal design of the klystron is electrodynamic system providing high output power about 100 MW and high power gain about 80 dB. It is evident that these requirements are conflicting ones. The requirement of a high output power forces one to increase the aperture in order to provide a high value of the operating current at a moderate electron beam quality and limited voltage. On the other hand, the danger of parasitic self-excitation increases at increasing the aperture and operating current, because the frequencies of parasitic modes become quite close to the operating frequency and their increments grow with the beam current which makes the problem of the parasitic oscillation suppression more complicated.

These points formed the base of investigation which was started at the Budker Institute of Nuclear Physics more than ten years ago. The result of this investigation was the development of a concept of high gain, wide-aperture klystron. Experience with pilot devices has shown that the main problem to achieve designed goal was that of self-excitation of the klystron. To solve the problem of the parasitic modes suppression, we have studied two ways: the use of the wave chokes and the technique of permanent change of the phase velocity of the parasitic modes to decrease the interaction region of the beam with parasitic modes. Nevertheless, our experience have shown that these techniques do not provide the desired results, especially, in the case of a high gain ($\sim 70 - 80$ dB).

In Refs. [11,12] we have proposed another idea to suppress parasitic oscillations which consists the use of RF absorbing drift tubes for distributed suppression of parasitic oscillations. We have upgraded the 11 mm aperture klystron with RF absorbing insertions and performed the study of amplification regime. As a result, all the self-excitation modes have been suppressed. In a long pulse (250 ns), we have achieved a value of the output RF power about of 45 MW at the beam current $I \sim 150$ A which corresponds to a klystron efficiency ~ 30 %. This result is in good agreement with calculations. In a short pulse, we have achieved a peak value of the RF output power of about 70 MW. Damage of output structure and wave transformer due to high level of RF power forced us to stop experiments with this klystron [12].

In this paper we present the results of amplification experiments with wide-aperture (15 mm) VLEPP klystron.

2 Design of the klystron

The goal of the design was to develop a high-aperture klystron. As a rule, designers of the klystron consider several ranges of the aperture size. The first one corresponds to a size of the aperture for which the cut-off frequency is less than the doubled operating frequency. For the frequency of 14 GHz this corresponds to the minimal aperture of the klystron of 6.28 mm. This ratio of the aperture to the wavelength is generally accepted for the S-band klystrons, but it is too small for the high-power X-band klystrons. The upper boundary of second range corresponds to the cut-off of the operating frequency.

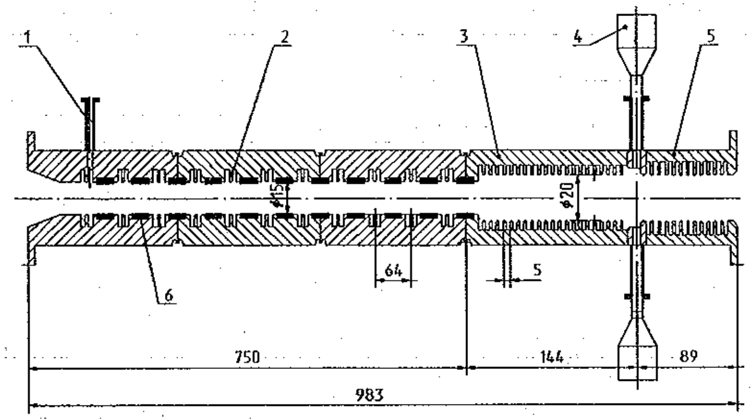


Fig. 1. Layout of the klystron with RF absorbing insertions. (1) – input waveguide, (2) – resonators of buncher, (3) – output structure, (4) – RF load, (5) – RF filter for E_{01} mode, (6) – RF absorbing insertions (placed inside drift tubes).

For the frequency of 14 GHz this corresponds to the minimal aperture of the klystron of 12.56 mm. This range has been accepted for the previous VLEPP klystron design (aperture 11 mm [8]). The lower and upper boundaries of the third band correspond to the cut-off frequencies for TE and TM modes, respectively. For the frequency of 14 GHz this corresponds to the minimal aperture of 12.56 mm and maximal – 16.4 mm.

In the present design we have chosen the aperture of 15 mm corresponding to the third aperture range. Parameters of the klystron have been optimized using different numerical codes [13]. As a result, we have chosen the following parameters (see Table 1 and Fig. 1). Operating voltage of the klystron is 1 MV, operating current is 250 A. Klystron buncher consists of 11 cavities spaced by 64 mm. The output structure is manufactured as corrugated waveguide and operates at $\pi/2$-mode. Total length of the electrodynamic structure is equal to 0.7 m. A saturation power of 100 MW is achieved at an input power of about 1 W (which corresponds to the power gain about of 80 dB). In Figs.2 and 3 we present calculated amplitude and frequency characteristics of the klystron.

The large aperture of the drift tubes (15 mm) helps to increase acceptance of the klystron. Nevertheless, there is one harmful consequence of a large aperture – the ground TE_{11} waveguide mode is not cut-off one for this klystron. As a result, the self-excitation of the klystron in the 14 GHz frequency band will occur due to the positive feedback for TE_{11} mode. The symmetric TM_{010} mode of the buncher and TE_{11} mode are coupled due to the radial misalignment of resonators in the process of their assembling and soldering, as well as due to asymmetric loading of two power outputs.

Table 1
Parameters of wide-aperture VLEPP klystron

General parameters	
Beam voltage	1 MeV
Beam current	250 A
RF frequency	14.0 GHz
Power gain	80 dB
RF peak output power	100 MW
Efficiency	40 %
Focusing system	
Type of magnets	Permanent magnet
Max. Magnetic field	4.5 kGs
Period	64 mm
Number of periods	14.5
Acceptance	0.1π cm·rad
Buncher	
Drift tube diameter	15 mm
Length of drift section	52 mm
Number of drift sections	10
Length of cavity	12 mm
Number of cavities	11
Mode of operation	π
Output structure	
Mode of operation	$\pi/2$
Number of cells	22
Length	110 mm
Aperture	20 mm

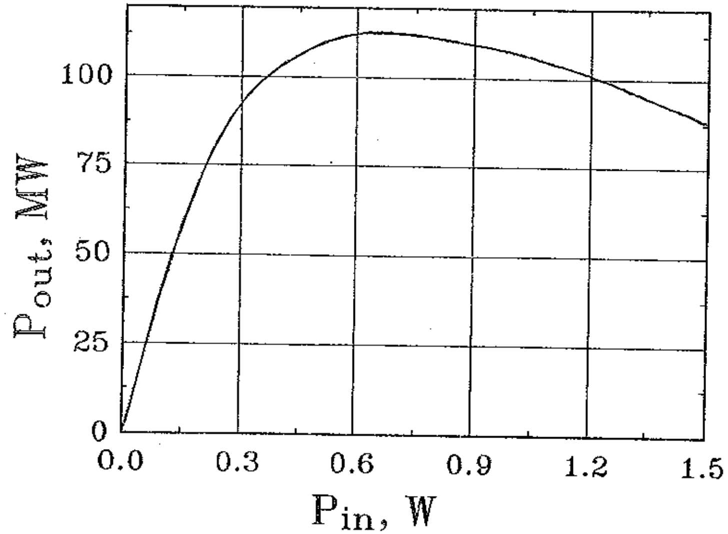


Fig. 2. Amplitude characteristic of the klystron (calculations).

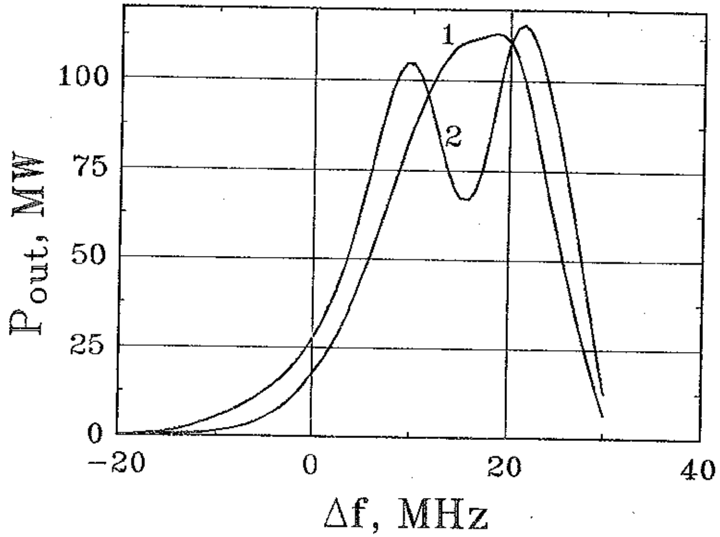


Fig. 3. Frequency characteristic of the klystron (calculations). Curve 1 – $P_{in} = 0.5$ W, curve 2 – $P_{in} = 1$ W. Here $\Delta f = f - 14$ GHz.

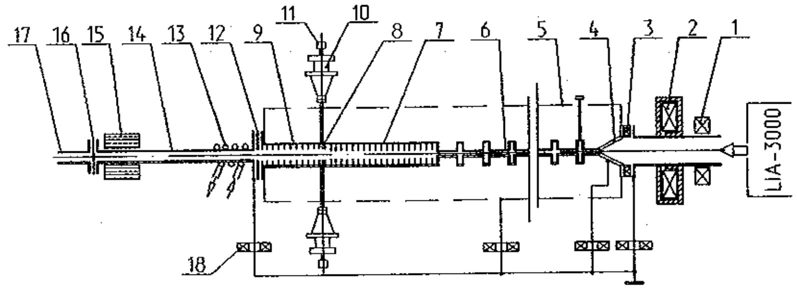


Fig. 4. Experimental setup (1 – dipole magnet, 2 – short magnetic lens, 3 – isolator, 4 – Ti cone, 5 – relativistic klystron, 6 – buncher, 7 – output structure, 8 – wave transformer, 9 – RF filter, 10 – RF load, 11 – RF detector, 12 – isolator (0.3 mm synthetic film), 13 – beam collector cooler, 14 – beam collector, 15 – dipole magnet, 16 – vacuum window (0.3 mm synthetic film), 17 – circular waveguide, 18 – Rogowsky coils).

3 Experimental setup

Investigations have been performed at JINR using the driving beam of the LIA-3000 induction accelerator (energy 1 MeV, beam current up to 250 A, beam emittance 0.05π cm·rad, pulse duration 250 ns). The beam was matched with the klystron magnetic system by means of focusing lenses (2) and dipole magnets (1), and the cone Ti diaphragm (4) of 15 mm diameter was placed prior to the klystron entrance (see Fig.4). The beam current monitors (18) provided the possibility to measure the beam current at the accelerator exit, entrance and exit of the klystron and the beam current losses inside the klystron. To obtain a more detailed information about the RF radiation, we have used a beam collector in a form of circular waveguide of 20 mm diameter. Dipole magnet (15) deflected the electron beam and prevented the damage of the output window (16) made of thin polymer film.

4 Electron beam transport

The focusing system of the klystron is manufactured on the base of permanent magnets (Nd-Fe-B). To study the beam dynamics in the focusing system, we have screened the beam from the electromagnetic structure of the klystron by a thin-wall Ti tube. The transverse beam dimensions were measured using the thin Al and Pb films placed inside the electron transport channel. The value of exposition (number of shots) has been defined at the condition for the electron beam to burn a hole in the film and pass through this hole without losses. The size of the hole corresponds to the electron beam size (see Fig.5).

Measurements have shown that the focusing structure was manufactured with the appropriate accuracy. Less than 5 % of the accelerator current was lost at the cone diaphragm,

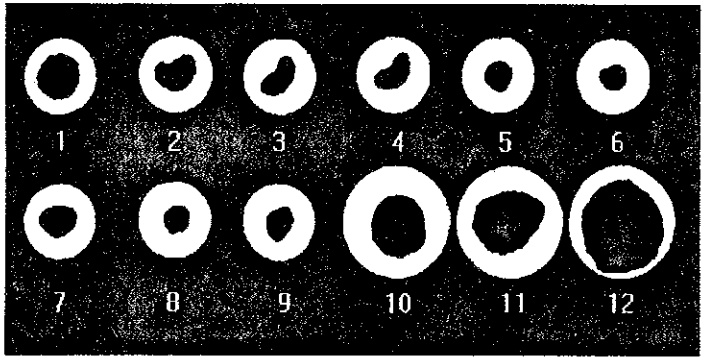


Fig. 5. Beam size in the focusing system of the klystron. Points 1 through 9 correspond to the buncher (15 mm aperture), points 10 and 11 – the output structure (20 mm aperture) and point 12 – the wave transformer (20 mm aperture).

and there were no losses of the current in the buncher and the output structure. The value of the beam current in the collector was 250 A. The beam envelopes in the klystrons were in good agreement with calculations.

When the screening tube was withdrawn off the klystron, there were unexpected losses of the beam current in the output structure. We explain this phenomenon as a strong action of the space charge fields of the bunched electron beam. To overcome this problem, we have mismatched the electron beam to provide a larger value of the beam envelope in the output structure (see Fig.5). As a result, the beam losses in the output structure are eliminated.

5 Study of self-excitation regime

The self-excitation regime has been examined in three stages: study of the self-excitation modes of buncher (at the screened output structure); the study of the self-excitation modes of the output structure (at screened buncher) and the study of the self-excitation modes of klystron.

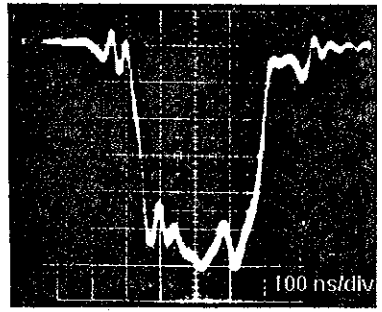
The self-excitation of the buncher takes place at frequencies:

$$13.9\ \text{GHz} \lesssim f \lesssim 14.15\ \text{GHz}, \qquad f_1 = 14.04\ \text{GHz}$$
$$16.3\ \text{GHz} \lesssim f \lesssim 16.50\ \text{GHz}, \qquad f_2 = 16.40\ \text{GHz}$$

and their harmonics. The self-excitation modes of the output structure were not detected.

Our study has shown that the self-excitation of the klystron in the 14 GHz frequency band is determined by the positive feedback for TE_{11} mode. The central frequency of these oscillations is almost independent of the electron beam energy and depends significantly on the beam current. The self-excitation at 16.4 GHz takes place at TM_{01} mode which corresponds to the calculated mode of the second resonance of the buncher. The modes

(a)



(b)

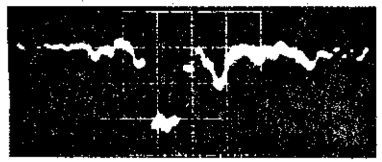


Fig. 6. Oscillogram of the self-excitation. (a) - the beam current in the collector, (b) - RF signal from the wide band detector.

of the $f_1 = 14$ GHz frequency band have maximal increments. Within limitations of the pulse duration (250 ns) we have not obtained a threshold behaviour of the self-excitation. At a high beam current it takes place at the beginning of the pulse and when the current is decreasing, a detectable amplitude of the self-excitation occurs at a longer time after the pulse beginning.

More thorough investigations have shown a complicated temporal behaviour of the self-excitation regime. In Fig.6 we present typical oscillograms. It is seen from Fig.6a that there are significant fluctuations of the beam current in the collector. This is connected with the significant losses of the current in the klystron and indicates the existence of transverse beam instabilities. Fig.6b shows the time dependency of the output klystron power obtained with the wide band detector. Thorough investigations with a narrow band detector have shown that the self-oscillation spectrum is not fixed but evolves significantly in time (two maxima in Fig.6b correspond to different frequencies). The self-excitation process has appearance of a mode competition process. The self-excitation develops from the 14 GHz mode having maximal increment and then it stimulates the growing of TM_{01} mode at 16.4 Ghz frequency. The growing of the latter mode leads to suppression of the "parent", 14 GHz mode. Oscillograms in Fig.6 illustrate this process. In Fig.6a we obtain two regions of the beam current losses which correspond to the moments of time when 14 GHz and 16.4 GHz modes reach their maxima.

The presence of the signal from master oscillator (TWT) does not change the situation. At low beam current ($I \lesssim 50$ A) we have obtained the nominal regime of amplification. When the beam current was increased, the self-excitation occurred at the back front of the beam current and the duration of the amplification stage was shortened with the beam current increase. At the beam current value about of 250 A, the self-excitation process appeared from the beginning of the pulse.

6 Upgrading of the klystron with RF absorbing drift tubes

In Refs. [11,12] we have proposed an idea to suppress parasitic oscillations which consists the use of RF absorbing drift tubes for distributed suppression of parasitic oscillations. The main idea of this approach is to find such a klystron design where the increments of parasitic modes are less than their attenuation in the klystron. We have realized this concept in the following way. We have developed technology of RF attenuating insertions and placed them inside the drift tubes of the klystron (see Fig.1 and 7). We have studied several methods to obtain absorbing materials. Investigations have shown that glass-carbon materials are more simple for manufacturing and have used in our equipment.

Such a distributed suppression filter provides significant attenuation of the parasitic modes and does not perturb the klystron operating mode (see Fig.8). Operating experience has shown that insertions do not affect vacuum conditions and are stable to the heat and radiation load.

We have expected also that the insertions may cause resistive instabilities of the beam. Nevertheless, thorough investigations of the beam dynamics have not shown any evidence of such instabilities.

In the same way as it has been described in the previous section, we have performed the study of the self-excitation mode of operation. It was found that all parasitic modes of the self-excitation have been totally suppressed.

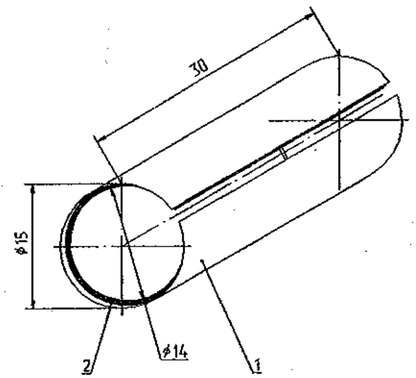


Fig. 7. Scheme of RF absorbing insertions. (1) – metal foil, (2) – RF absorbing layer.

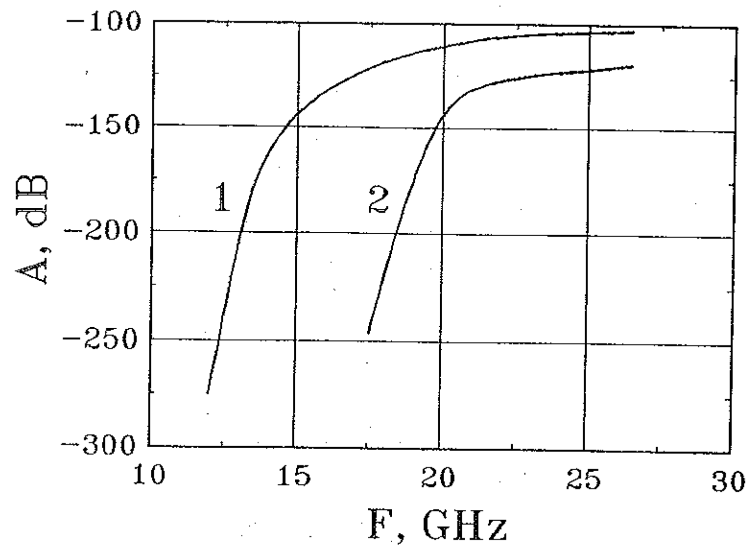


Fig. 8. Integral frequency characteristic of the distributed suppression filter composed of ten RF absorbing insertions (1 – H_{11} mode and 2 – E_{01} mode).

7 Study of the amplification regime

After upgrading of the klystron with RF absorbing insertions, we have performed the study of the amplification regime. The master signal was generated by the travelling wave tube. Typical oscillograms of amplification mode of operation are presented in Fig.9. One can see from Fig.9a that there are no fluctuations of the beam current in the collector, which indicates the absence of transverse beam instabilities. We have measured the frequency spectrum of the output radiation and have not observed any frequencies except of operating frequency 14 GHz.

At the beginning of operation at an output power level of about 10 MW we have found that there are temporal instabilities in the form of output signal. At further increasing of the output power we found a shortening of the RF pulse with respect to the beam current pulse. This is connected with the RF discharges in the output structure. During RF training procedure [12] we have gradually increased the value of the output power and after 10^5 pulses we have reached 75 MW output power within a pulse length of 250 ns (maximal pulse length of the accelerator). Upon achieving this level of output power, the efficiency of training diminished significantly [11]. We began to study the origin of this

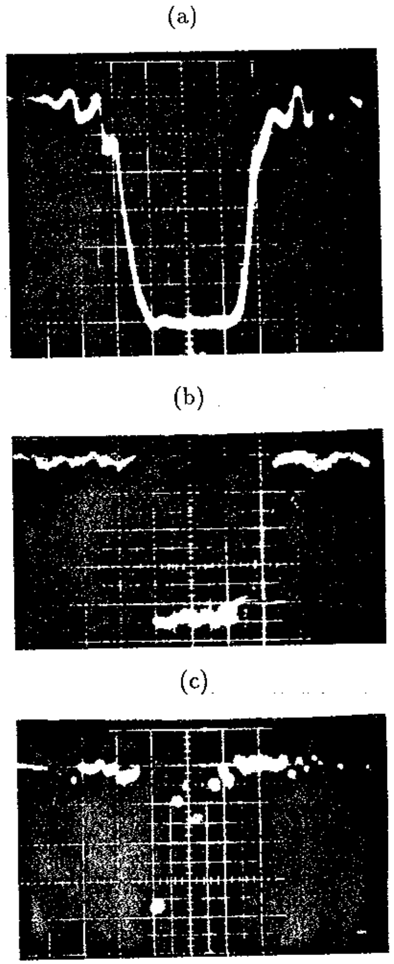


Fig. 9. Oscillogram of the amplification regime. (a) - the beam current in collector, (b) - RF signal after RF training cycle, (c) - RF signal at the beginning of the next RF training cycle.

effect and found that it was connected with RF breakdown in the RF load, but not with the output structure of the klystron. After upgrading the RF load we immediately reached the designed output power of 100 MW within a pulse length of 250 ns. In Figs.10 and 11 we present amplitude and frequency characteristics of the klystron. one can see that there is good agreement between theoretical and experimental results (see Figs.2 and 3).

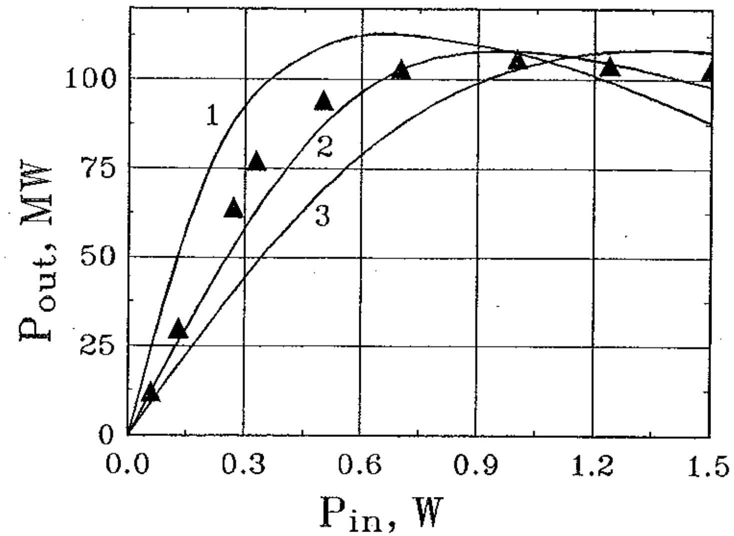


Fig. 10. Amplitude characteristic of the klystron. Here ▲ - experimental results and curves - theoretical calculations (1 - $U = 1$ MV, 2 - $U = 1.025$ MV, 3 - $U = 1.05$ MV).

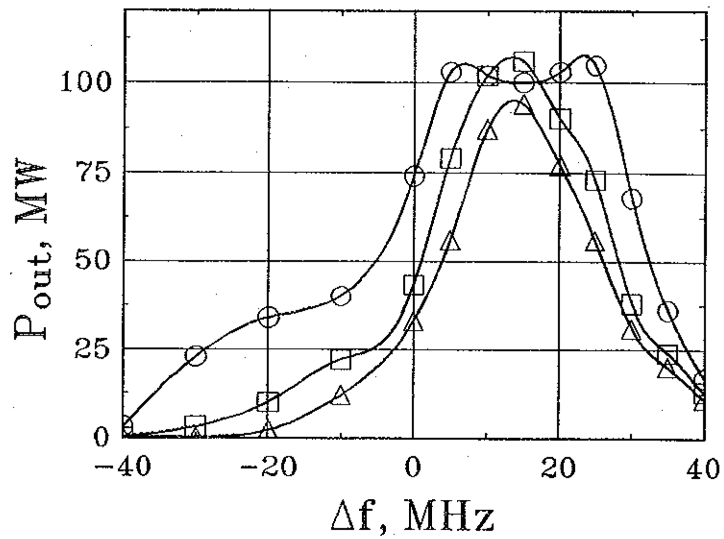


Fig. 11. Frequency characteristic of the klystron. △ - $P_{in} = 0.5$ W, □ - $P_{in} = 1$ W and ○ - $P_{in} = 2$ W ($\Delta f = f - f_0$, where $f_0 = 14$ GHz).

8 Conclusion

In this paper we developed the concept of a klystron with distributed suppression of parasitic modes. Particular feature of the present experiment is that we proved experimentally a possibility to construct wide-aperture klystrons with an aperture comparable with the RF wavelength. Such a klystron design possesses significant advantages with respect to the standard design, revealing the perspective of increasing operating current and, as a result, peak output power. We believe that wide-aperture klystrons with RF absorbing drift tubes can form a novel direction in the design of short RF wavelength klystrons.

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