Achievement of 100 MW Output Power in a Wide Aperture VLEPP Klystron with Distributed Suppression of Parasitic Modes

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Abstract. In this paper we present the results of experimental study of a wide aperture (15 mm), high gain (80 dB) VLEPP klystron upgraded with RF absorbing insertions. Investigations have been performed using the driving beam of the JINR LIA-3000 induction accelerator ($E = 1$ MeV, $I = 250$ A, $\tau = 250$ ns). The proposed technique for suppressing parasitic self-excitation proved to be extremely fruitful: we have obtained design output parameters of the klystron and achieved level of 100 MW output power.

INTRODUCTION

The klystron for linear collider 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 one hundred pps or higher [1].

The cost of the RF system constitutes significant fraction of the total cost of the linear collider. 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 [2]. The most cheapest modulator is considered in the VLEPP project [3]. This concept is based on the use of distributed high-voltage power supply. The control of the beam current is performed by means of gridded electron gun [2]. Providing the most cheapest design of the modulator, 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 and phase stability becomes more severe at higher level of RF power. Remembering that peak power of the klystron should be of the order of 100 MW, we may conclude that the choice of the power gain of 80 dB is the most optimal one.

It is evident that the requirements of high output power and high power gain are conflicting ones. The requirement of a high output power forces 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, at the increasing of the aperture and operating current, the danger of parasitic self-excitation is increased, 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 (~ 70 – 80 dB).

In papers [5, 6] we have proposed another idea to suppress parasitic oscillations which consists in 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 the value of the output RF power about of 45 MW. In a short pulse, we have achieved the peak value of the RF output power about of 70 MW. A damage of output structure and wave transformer due to high level of RF power forced us to stop experiments with this klystron [6].

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

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 such size of the aperture which provides the cut-off frequency to be 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 klystrons of S-band, 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. 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 [2]). 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 [7]. 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 – 250 A. Klystron buncher consists of 11 cavities spaced by 64 mm. 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. Saturation power of 100 MW is achieved at the input power about of 1 W (which corresponds to the power gain about of 80 dB).

The large aperture of drift tubes (15 mm) helps to increase acceptance

TABLE 1. Parameters of the 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

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 is occurred due to the positive feedback for TE_{11} mode. 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 the unsymmetrical loading of two power outputs.

In papers [5, 6] 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

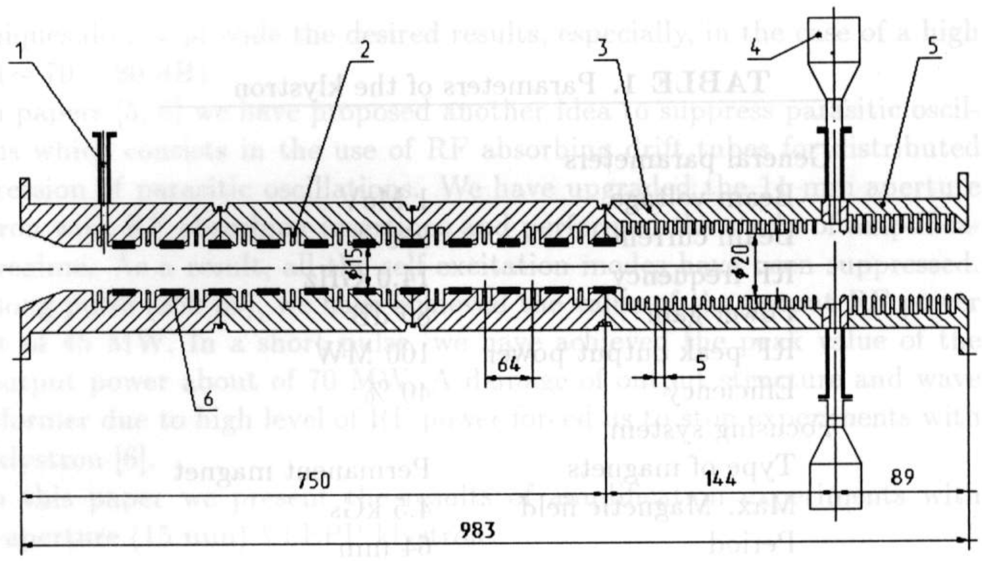

FIGURE 1. Layout of the klystron with RF absorbing insertions. Here (1) – input waveguide, (2) – resonators of buncher, (3) – output structure, (4) – RF load, (5) – RF filter for E_{01} mode, (6) – RF absorbing insertions (placed inside drift tubes).

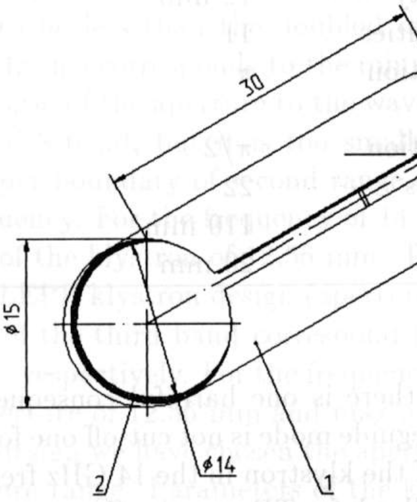

FIGURE 2. Scheme of RF absorbing insertions. Here (1) – metal foil, (2) – RF absorbing layer.

attenuation in the klystron. We have developed technology of RF attenuating insertions and placed them inside the drift tubes of the klystron (see Fig.1 and 2). We have studied several methods to obtain absorbing materials. Investigations have shown that glass-carbon materials are more simple for

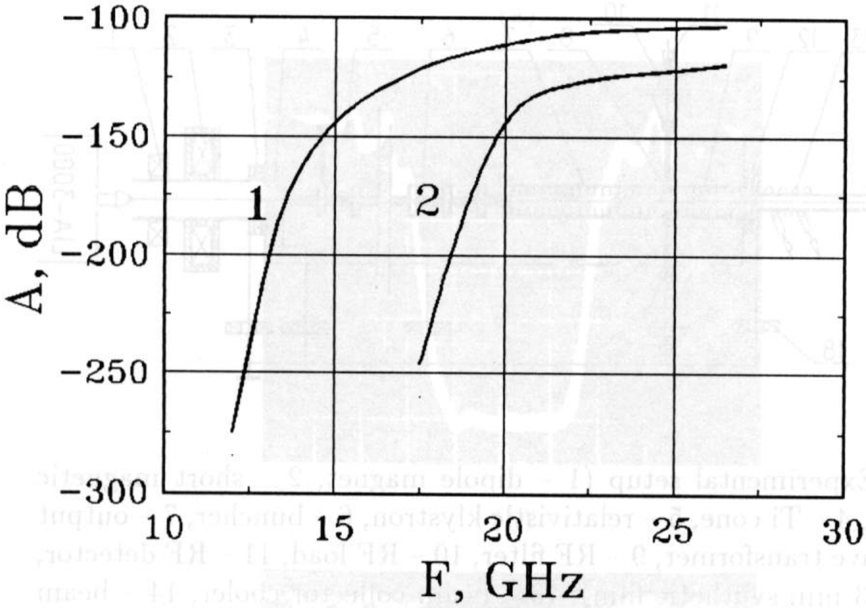

FIGURE 3. Integral frequency characteristic of the distributed suppression filter composed of ten RF absorbing insertions (1 – H_{11} mode and 2 – E_{01} mode).

manufacturing and use 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.3).

Operating experience has shown that insertions do not affect vacuum conditions and are stable to the heat and radiation load. Investigations of the beam dynamics have not shown any evidence of resistive instabilities of the beam caused by these insertions.

EXPERIMENTAL SETUP

Investigations have been performed at JINR using the driving beam of 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 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

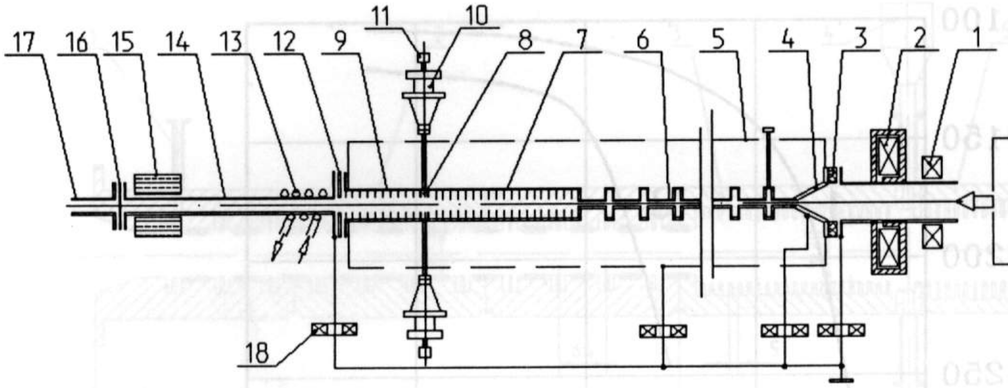

FIGURE 4. Experimental setup (1 – dipole magnet, 2 – short magnetic lens, 3 – isolator, 4 – Ti cone, 5 – relativistic klystron, 6 – buncher, 7 – output structure, 8 – wave transformer, 9 – RF filter, 10 – RF load, 11 – RF detector, 12 – isolator (0.3 mm synthetic film), 13 – beam collector cooler, 14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

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.

Measurements have shown that less than 5 % of the accelerator current was loosed at the cone diaphragm, and there were no losses of the current in the klystron. The value of the beam current in the collector was 250 A.

STUDY OF AMPLIFICATION REGIME

We have performed the study of amplification regime of the klystron upgraded with RF absorbing insertions. The master signal was generated by the travelling wave tube. Typical oscillograms of amplification mode of operation are presented in Fig.5. It is seen from Fig.5a that there are no fluctuations of the beam current in the collector which indicates on the absence of the 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 the level of output power of about 10 MW we have obtained that there are temporal instabilities in the form of output signal. At further increasing of the output power we have obtained shortening of the RF pulse with respect to the beam current pulse. This is connected

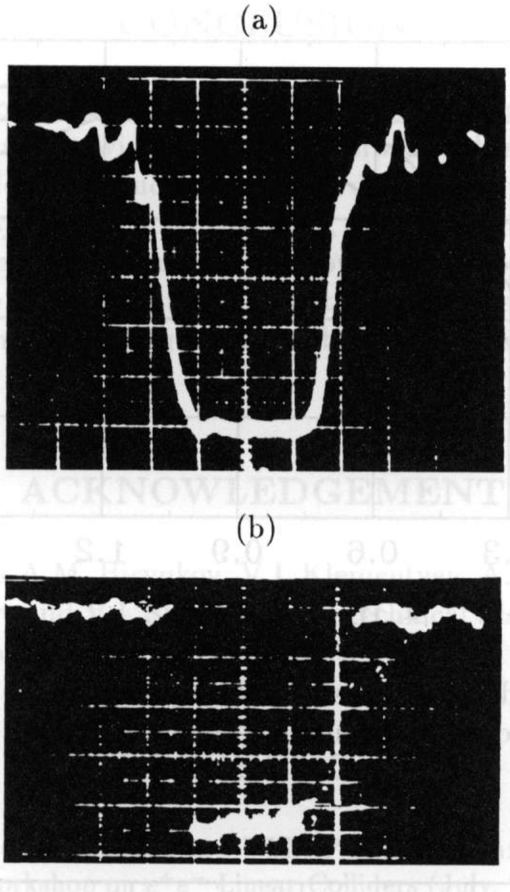

FIGURE 5. Oscillogram of the amplification regime. Here (a) – the beam current in collector, (b) – RF signal corresponding to 100 MW output power.

with the RF discharges in the output structure. During RF training procedure [6] we have gradually increased the value of the output power and after 10^5 pulses we have reached 75 MW output power within the pulse length of 250 ns (maximal pulse length of the accelerator). Upon achieving this level of output power, efficiency of training diminished significantly [5]. We began to study the reason of this effect and obtained 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 designed output power of 100 MW within the pulse length of 250 ns. In Figs.6 and 7 we present amplitude and frequency characteristics of the klystron. There is good agreement between theoretical and experimental results.

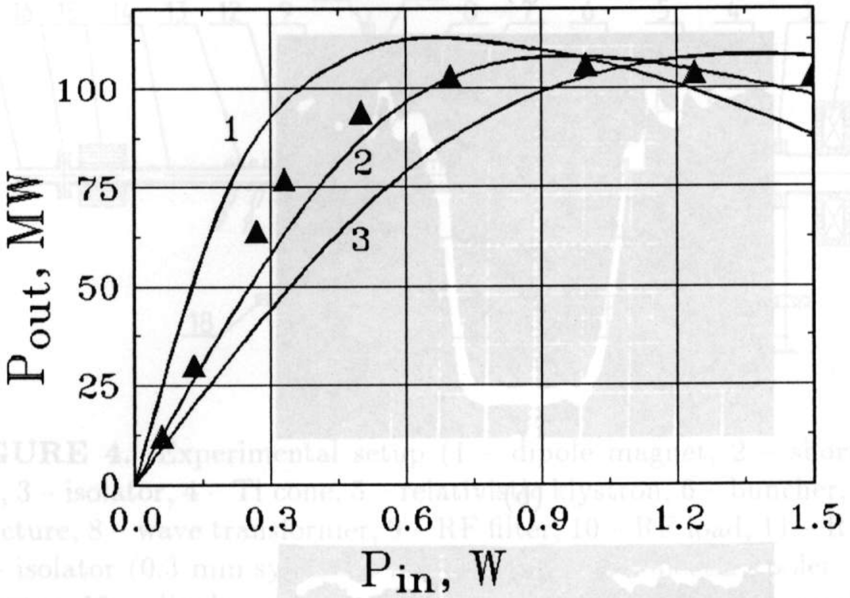

FIGURE 6. Amplitude characteristic of the klystron. Here ▲ – experimental results and curves – theoretical calculations (1 – $U = 1$ MV, 2 – $U = 1.025$ MV, 3 – $U = 1.05$ MV).

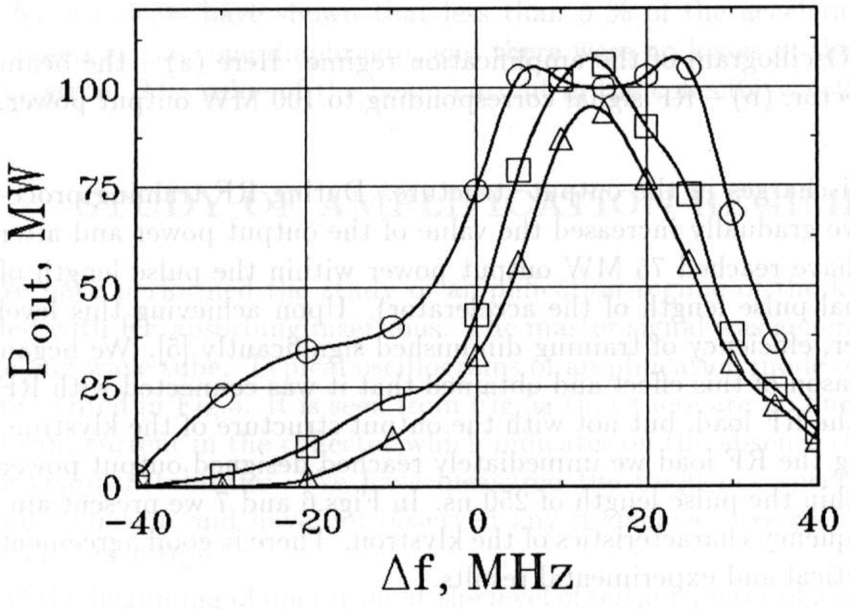

FIGURE 7. Frequency characteristic of the klystron. Here △ – $P_{in} = 0.5$ W, □ – $P_{in} = 1$ W and ○ – $P_{in} = 2$ W ($\Delta f = f - 14$ GHz).

CONCLUSION

The main result of the present experiment is that we proved experimentally a possibility to construct wide-aperture klystrons with aperture comparable with the RF wavelength. Such a klystron design seems to be optimal for the use in the RF system of linear colliders, because it reveals perspective of increasing operating current (and output power) at a moderate quality of the electron beam. We believe that wide-aperture klystrons with RF absorbing drift tubes can form a novel direction in the design of short RF wavelength klystrons for linear colliders.

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